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Abundance of Atlantic salmon (*Salmo salar*) in the Big Salmon River, New Brunswick, from 1951 to 2002

Abondance du saumon atlantique (*Salmo salar*) dans la rivière Big Salmon, au Nouveau-Brunswick, de 1951 à 2002

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Abstract

Atlantic salmon of the Big Salmon River, New Brunswick, are part of a larger population assemblage, known as "inner Bay of Fundy Atlantic salmon", that is currently listed as endangered by COSEWIC. The Big Salmon River population has been impacted by human activities for over 150 years and has been the focus of recovery efforts intermittently for more than 70 years. We compile data from the Big Salmon River stock collected since 1951 and use these data to assess changes in population size since that time. We used maximum likelihood to model the catch-effort, juvenile electrofishing, adult fence, stream-side and dive counts, and redd count data, to obtain estimates of the annual escapements and returns during this time period. While none of the four models presented are entirely satisfactory, all indicate a spawning run size in the range of 1,000 to 4,000 salmon during the 1960's and early 1970's, and a spawning run size of less than 100 fish since 1996. Estimates of the percent decline from the early 1990's ranged between 63% and 80%, and between 92% and 97% over the last 30 years.

Résumé

Le saumon atlantique retrouvé dans la rivière Big Salmon, au Nouveau-Brunswick, fait partie d'un assemblage plus large, connu sous l'appellation « population de saumon atlantique de l'intérieure de la baie de Fundy », qui a été désigné par le COSEPAC comme étant en voie de disparition. La population de la rivière Big Salmon est soumise aux activités humaines depuis plus de 150 ans et a été l'objet d'efforts de rétablissement intermittents pendant plus de 70 ans. La compilation des données recueillies sur ce stock depuis 1951 nous a permis d'établir l'évolution de la taille de la population au cours de la période allant de 1951 à 2002. Nous avons utilisé la méthode du maximum de vraisemblance pour modéliser les prises par unité d'effort, le nombre de juvéniles pêchés par pêche électrique, le nombre d'adultes observés aux barrières de dénombrement (des rives et en plongée), et les données de dénombrement des nids de fraie, ce qui nous a permis d'obtenir des estimations des échappées et des remontes annuelles durant cette période. Bien qu'aucun des quatre modèles présentés ne soit entièrement satisfaisant, ils indiquent tous que la taille des remontes se situait entre 1 000 et 4 000 saumons pendant les années 1960 et au début des années 1970 et qu'elle se chiffre à moins de 100 individus depuis 1996. Les estimations du déclin en pourcentage depuis le début des années 1990 varient entre 63 et 80 % et, au cours des trois dernières décennies, entre 92 et 97 %.

Introduction

Atlantic salmon (*Salmo salar* L.) of the Big Salmon River (BSR), New Brunswick, are part of a population assemblage of salmon designated "endangered" by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). This assemblage, deemed "inner Bay of Fundy (iBoF) Atlantic Salmon" includes salmon native to rivers in the Bay of Fundy, north of the Saint John River, NB, and north of the Annapolis River, NS, exclusive of these rivers. The salmon population in the BSR, similar to many iBoF rivers is comprised of mostly fish that mature after one winter at sea (1SW[1]) and repeat-spawning 1SW salmon.

The BSR Atlantic salmon population has been the focus of ongoing recovery efforts. The river was dammed during the mid 1800's by sawmills (Perley 1852) blocking access for salmon to spawning areas. These dams were breached, leading to restoration of the salmon run, and then rebuilt in the 1920's to create a log storage pond. A fishway bypassing the dam was built in the early 1930's, and the river was stocked with juvenile salmon from the late 1930's to 1973. Over 2.7 million juvenile salmon were released into this river between 1930 and 1973 (Gibson et al. 2003). The dam and fishway were removed in 1963 (Jessop 1986).

Marshall et al. (1992) determined the spawning (conservation) requirement for the Big Salmon River to be 2.2 million eggs based on an egg deposition rate of 2.4 eggs/m^2 of accessible habitat. Based on the biological characteristics of the BSR population, this requirement could potentially be met by 280 maiden 1SW, and 420 two-sea-winter (2SW) and repeat-spawning 1SW salmon (Marshall et al. 1992).

The age distribution of returning adults has been reported by Jessop (1986) and Amiro and McNeill (1986) and indicates a small (4%) 2SW component. Sampling for ages in recent years has occurred during broodstock sampling in 1989 and 1990 and from samples obtained by seining fish during mark-recapture experiments. With the exception of 1989, the sample sizes are small and are unlikely to reflect the age structure of the returns in those years. The majority (75%) of the forty-five fish sampled during broodstock collections in 1989 were maiden 1SW fish (O'Neil et al. 1989) supporting the idea that the majority of fish in this population mature after one winter at sea.

Salmon of the BSR were the focus of a 10-year study beginning in 1964. Characteristics of the population and fishery during this period were described by Jessop (1975, 1986). Our purpose in producing this document was to summarise more recent data collections for BSR salmon and use the data to evaluate the current status of the population. In so doing, estimates of changes in population size during the last four decades, as well as estimates of the harvest rates for the recreational fishery on this river are also provided.

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[1] Several terms are used describe adult salmon within this document, some of which are loosely equivalent. Salmon that have returned to the river to spawn for the first time after one winter at sea are referred to as one-sea-winter (1SW) salmon, fish that return as maiden fish after two winters at sea are referred to as two-sea-winter (2SW) salmon and fish that return after more than two years are termed multi-sea-winter (MSW) salmon. Very few maiden MSW salmon have been reported from the Big Salmon River. A repeat-spawning salmon is a salmon that has spawned one or more times previously. The recreational catch is reported as large (fork length $\geq$ 63 cm) and small ($<$ 63 cm) salmon. Large salmon may be 2SW or MSW fish, or may be repeat-spawning 1SW fish. Small salmon are maiden 1SW fish or repeat-spawning 1SW fish.

Data

Data for the BSR salmon consist of:

- recreational fishery catch and effort data for 1951 to 1990,
- counts of fish ascending a fishway for 1954 to 1962 and at a counting fence for 1964 to 1973,
- counts and adjusted escapement estimates from shoreline observation and dive counts for 1988 to 2002,
- redd counts from sections of the river in 1996 to 2002,
- estimates of smolt abundance obtained at a counting fence during 1966 to 1971 and by mark-recapture with a rotary screw trap or smolt wheel in 2001 and 2002, and
- estimates of juvenile densities obtained by electrofishing in 1968, 1970 to 1973, 1982 and 1989 to 2002.

None of the data sets span the full time period under investigation.

Recreational fishery data

The reported landings and fishing effort for the recreational fishery on this river are available for the years 1951 to 1990 (Jessop 1986, Swetnam and O'Neil 1985, O'Neil and Swetnam 1984, O'Neil and Swetnam 1991, DFO Atlantic salmon angling statistics database). These data are provided here in Table 1 and Figure 1. Prior to 1964, the landings were recorded as the total number of salmon taken in the fishery. Since 1964, the landings were subdivided into the number of small and large salmon. No landings of large salmon have been reported since a hook and release policy was implemented for large salmon in 1984, and no landings of small salmon have been reported since the closure of this fishery in 1990.

The fishing effort peaked in 1960 at 41,317 rod days, and high values were reported in 1961, 1962 and 1983 (Table 1; Figure 1). During this time period, the catch and effort were estimated by local fisheries officers who may or may not have developed familiarity with the local fisheries (O'Neil and Swetnam 1991). Other than these data points, effort was highest in the late 1970's and early 1980's. Reported landings loosely track the effort time series, with peaks in mid 1960's and late 1970's (Table 1; Figure 1).

Fishway and fence counts

Counts of salmon, size groups combined, are available for the years 1954 to 1962 (Table 1; Figure 2). These counts were obtained at a fishway that allowed salmon to ascend a logging dam at the head of the tide (Jessop 1986). The counts ranged between 95 and 1,767 salmon annually.

Counts of salmon were obtained at a counting fence near the mouth of the river during 1964 to 1973 (Jessop 1986). Jessop (1986) adjusted the counts during years in which the fence was breached during high water events. Between 872 and 5,224 salmon returned to the Big Salmon River annually during this time period (Table 1, Figure 2). Jessop (1986) describes the Big Salmon River adult salmon as a late summer run, generally peaking from mid-August to mid-September. With the exception of 1968, the majority of the salmon were captured at the counting fence prior to mid-October.

Shoreline observation and dive counts

Since 1988, the New Brunswick Department of Natural Resources and Energy (NBDNRE) and the Department of Fisheries and Oceans have conducted counts of the number of fish in the river by streamside observation and by dive counts (Table 2; Appendix 3). In some years these counts were adjusted and used an estimate of the spawning escapement. For example, Amiro and Jefferson (1996) adjusted the 1995 streamside count upwards using the proportion of the total river surveyed (15 pools surveyed representing 74% of the available habitat) and using an estimated observation rate of 90-95%. The highest escapement count was in 1989 (975 salmon) while the lowest was in 2001 (30 salmon) (Table 2; Figure 2). Since 2000, attempts to estimate the number of returning adults using mark-recapture techniques have been unsuccessful, either due to high water or failure to tag sufficient numbers of adults. Details of these surveys are summarized in Appendix 3 and the pools and river sections included in the surveys are shown in Figure 3.

Age data from returning adults has been reported in Jessop (1986) and Amiro and McNeill (1986). These data indicate a small (4%) maiden 2SW component. Sampling for age distribution since the counting fence operation ceased after 1973 includes broodstock sampling in 1989 and 1990 and samples obtained by seining fish during mark-recapture experiments for the purpose of estimating the number of returning adults. With the exception of 1989, the sample sizes are small and are unlikely to reflect the age structure of the returns in those years. The majority (75%) of the forty-five fish sampled during broodstock collections in 1989 were maiden 1SW fish (O'Neil et al. 1989).

Redd counts

Since 1996, NBDNRE has annually conducted salmon redd surveys in two sections of the river (Figure 5). These counts are another index of spawning escapement during this time period (Table 3; Figure 4). The survey covered about 45% of the accessible spawning area of the Big Salmon River headwaters and includes two sections that are considered prime spawning areas (T. Pettigrew pers. comm)[2]. Over the seven years, the count averaged 50 redds, ranging from 22 to 96 redds. We used the total number of redds observed annually as an index of spawning escapement for the analysis herein. The annual counts are not adjusted for the amount of area covered during each year.

Juvenile electrofishing surveys

The densities of age-0, age-1 and age-2 juvenile salmon have been estimated by electrofishing (Amiro and Longard 1995) for the years 1968, 1970 to 1973, 1982 and annually since 1989 (Table 4). Removal methods were used at three to five closed (barrier nets) electrofishing sites each year (Figure 5). With the exception of 1982, mean annual densities were less than 50 age-0 parr per $100m^2$, less than 20 age-1 parr per $100m^2$, and less than 12 age-2 parr per $100m^2$ (Table 4; Figure 6). Estimated densities of juveniles may not be indicative of wild production in some years due to stocking of unmarked, captive-reared age-0 or age-1 salmon the previous year (Table 4; Figure 6).

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Additionally, during 1994 and 1995, 397 (48% female) and 227 (67% female) captive-reared small salmon, respectively, were released into the Big Salmon River (Amiro and Longard 1995; Amiro and Jefferson 1996). Therefore, the higher age-0, age-1 and age-2 densities in the subsequent years may partially be the result of these releases. In 1994, a small portion of these cage-reared 1SW salmon were released in Falls Brook (above an impassable barrier to salmon) to monitor spawning success. Observed redds in 1994 and fry the following summer confirmed successful spawning and hatching to the fry stage (Amiro and Jefferson 1996). In 1995, the caged-reared adults were released between Bridge and King pools (Figure 5). In 1996, high age-0 parr densities were observed at the three headwater sites (Anderson Brook, Schoals Dam, Crow Brook) located upstream of the release locations and one mid-river site (Mast Brow) (Figure 7).

Smolt abundance

The adult counting fence on the Big Salmon River was modified to monitor emigrating smolt during 1966 to 1971 (Jessop 1975). The fence counts, adjusted for fence efficiency, ranged from 11,150 (1967) to 29,630 (1970) (Figure 8). Department of Fisheries and Oceans with the assistance of Woodstock First Nation reinitiated smolt assessments on the Big Salmon River in 2001. A rotary screw trap or smolt wheel was installed at the Bridge Pool and later relocated to the Lodge Pool (Figure 3) and was used to capture, mark and sample about 20% the wild smolt run. A second wheel was installed in the Amateur Pool, the same location as the counting fence in the late 60's and early 70's, and provided the platform to sample the marked and unmarked smolt (Figure 3). The number of wild smolt emigrating from the Big Salmon River in 2001 was estimated as 5,300 (95% C. I.: 3,800 – 8,600) (DFO 2002). In 2002, the smolt wheel was again installed at the head of the Amateur Pool and its capture efficiency was determined by releasing a proportion of the captured smolt back upriver to the Lodge Pool. In addition, a population of captive-reared (Live Gene Bank) smolt also emigrated from the BSR in 2002. These captive-reared smolt consisted of those released as age-0 parr in the fall of 2001 and age-1 smolt released during the spring of 2002. The Big Salmon River smolt run in 2002 was estimated at 6,300 smolt (95% C.I.: 4,100 - 13,700), consisting of 4,300 wild and 2,000 captive-reared smolt (DFO 2003). The annual counts are provided in Figure 8.

The Model

We followed the approach of Gibson and Amiro (2003). A schematic of the model is provided in Figure 9. The equations for the model are described below and provided in Table 5. Numbers in brackets in the following text refer to the equation numbers in Table 5. We wanted to estimate the number of fish in each size category (*s; small, large)*, returning to the river to spawn in year t, denoted $N_{t,s}$, and to use these estimates to determine the present status of the population relative to the start of the time series. No information about the adult component of the population is available for several of the years. We therefore set up the model to estimate the total number of fish returning in each year, N_t, and the proportion of fish in each size category, p_s, assumed constant over years. $N_{t,s}$ is the product of these parameters (1).

Functional relationships

The catch in each year and size category, $C_{t,s}$, is related to $N_{t,s}$ through the instantaneous rate of fishing mortality for each size class and year, denoted $F_{t,s}$ (2). We assume that $F_{t,s}$ is a function of the fishing effort in year t, E_t, and is related through the catchability coefficient, q_s, and a shape parameter, b (3). If b=1, $F_{t,s}$ is proportional to E_t. We assumed all fish captured were removed from the population.

Escapement in each year and size class, $Esc_{t,s}$ is the catch in each year and size class subtracted from the number of fish returning to the river in each year and size class (4). The fence count in year t and size category s, $Fence_{t,s}$, corrected for the catch downstream of the fence, equals to the number of fish returning to the river in each size category and each year (5). The redd count in year t, $Redd_t$, is assumed to be a function of $Esc_{t,s}$ and the "observability" coefficient for redds, q_{redd} (6). During estimation, q_{redd} was not bounded at less than 1 to allow for the possibility that a fish might dig more than one redd, or for the possibility that redds might be misidentified. The shore and dive counts in year t, $swim_t$, are similarly related to $Esc_{t,s}$ through an "observability" coefficient for shore and dive counts, q_{swim} (7). Egg deposition in year t, $Eggs_t$, was calculated from $Esc_{t,s}$ and the size class specific fecundity, fec_s, of Big Salmon River salmon (8). We estimated the fecundity of Big Salmon River salmon using data from Amiro and McNeill (1986). Fecundities were 2,299 eggs per small salmon and 5,227 eggs per large salmon. These values were used as constants in this analysis. During 1994 and 1995, the 397 and 227 captive-reared small salmon released into the Big Salmon River were added to the spawning escapement when calculating egg deposition. We used the mean densities of juvenile fish in year t for three age categories ($P_{t,a}$, a = ages 0,1 and 2 year old parr), obtained by electrofishing, as an index of egg deposition in year t-a-1. A Beverton-Holt model was used as the functional density dependent relationship between egg deposition and the resulting number of fish in that cohort (Hilborn and Walters 1992). For each age, we estimate an asymptotic recruitment level, R_{0a}, and the slope at the origin, α_a, for the Beverton-Holt model (9).

Parameter estimation

Parameter estimates were obtained by minimizing an objective function (*O.F.V.*) that is the sum of the negative log likelihoods (Quinn and Deriso 1999) for the catch (ℓ_{catch}), the fence counts (ℓ_{fence}), the redd counts (ℓ_{redd}), shore and dive counts (ℓ_{swim}), and the juvenile electrofishing data ($\ell_{electro}$). We used lognormal error structures for all likelihoods as described in Myers et al. (1995). Observed values are superscripted with "obs" (equations 10 to 14 in Table 5). In these equations, n is the sample size for the corresponding data set and σ_x is the corresponding shape parameter (for a lognormal distribution, σ is the standard deviation of a normal distribution prior to exponentiation).

Initial attempts to estimate the σ's for all model components, and for all components except for the fence count, were unsuccessful. Myers et al. (1995) published spawner-recruit relationships for 15 populations and recruitment age categories for Atlantic salmon. For a recruitment age of 1, σ averaged 0.330 (n = 4; range: 0.293 to 0.402). Models were fit to single data sets for recruitment ages of 0 and 2, for which σ was estimated as 0.334 and 0.581 respectively. These estimates were similar to the estimated σ's when smolt was used

as the recruitment category (mean=0.329; n=5; range: 0.206 to 0.440). Based on their analyses, we set σ_a equal to 0.334 for a=0, 0.330 for a=1 and 0.580 for a=2. σ_{fence} was set equal to 0.25 to reflect a higher degree of certainty about the fence count data. In a similar analysis of index data for Stewiacke River salmon, Gibson and Amiro (2003) estimated $\sigma_{catch\,s}$ and $\sigma_{catch\,l}$ to be 0.91 and 1.0 respectively. We set $\sigma_{catch\,s}$ and $\sigma_{catch\,l}$ equal to 1.0 based on their analyses. σ_{redd} and σ_{swim} were set equal to 0.5 to reflect a less variable process than the fishing component of the model, but greater variability than in the fence counts.

The relative contribution of each log likelihood to the objective function (15) is controlled using a set of weighting values, λ_i, selected to keep any one part of the objective function from dominating the fit. In the final model versions, all weights were set equal to one.

We initially set up the model to estimate the log of the total escapement in each year (1964 to 2002; 39 parameters), the average proportion of small salmon in the population (one parameter), the catchability or "observability" coefficients for the recreational fisheries, redd counts, and shore/dive counts (four parameters) and the slope at the origin and asymptotic level for the three ages of fish in the electrofishing data (six parameters), for a total of 50 parameters. Subsequent modifications to the model are described below.

The model was programmed using AD Model Builder (Fournier 1996). AD Model Builder (ADMB) uses the C++ auto-differentiation library for rapid fitting of complex non-linear models, has Bayesian and profile likelihood capabilities, and is designed specifically for fitting these types of models.

Bayesian Analyses

Bayesian methods provide a powerful tool for assessing uncertainty in fisheries models (McAllister et al. 1994). Their applications in fisheries are reviewed by Punt and Hilborn (1997) and McAllister and Kirkwood (1998). The posterior probability distributions resulting from the analyses represent the uncertainty in model parameters that includes both uncertainty in their estimation as well as prior information about their values (Walters and Ludwig 1993). ADMB uses a Markov Chain Monte Carlo (MCMC) algorithm (Carlin and Louis 1996) to approximate the posterior distribution for parameters of interest. MCMC is a stochastic simulation method used to evaluate complex integrals in order to derive posterior distributions. ADMB uses the Metropolis Hastings algorithm (Chib and Greenberg 1995) to generate the Markov chain, using a multivariate normal distribution based on the variance-covariance matrix for the model parameters to generate the chain. If the chain is long enough, the posteriors will be reasonably well approximated. Here, 1,000,000 iterations were used after a burn in of 100,000 iterations. Every 1,000th iteration was sampled to derive the posterior distribution. This level of thinning was sufficient to ensure that autocorrelation in the chain was not problematic in a similar analysis for Stewiacke River salmon (Gibson and Amiro 2003).

Diagnostics

Whenever minimisation is used to estimate parameters in a nonlinear model, there is a possibility of convergence to local minima, rather than the global minimum. Many iterations of the model were run from several starting values and, within reasonable limits, the estimates were found to be robust with respect to starting values. Convergence of the Markov chain was evaluated by examining trace plots for both estimated and derived parameters, testing of autocorrelation in the Markov chain, and by comparing the 10^{th} and 90^{th} percentiles of simulated chains obtained by starting the chain at different values (Gamerman 2000). Convergence was also inferred by comparing posteriors based on the first 500,000 iterations with those based on the second 500,000 iterations.

Alternative Model Formulations

As will be seen in the results section, the full model (50 parameters) fits are not completely satisfactory. Maximum likelihood estimates and asymptotic standard errors could be obtained for most model formulations, although large standard errors together with lack of convergence and periodicity in the MCMC stochastic simulations indicated that some parameters were very poorly determined. The problem was:

1) Absolute abundance estimates are only available for the late 1960's and early 1970's.
2) Abundance estimates for the late 1970's and early 1980's are based on the relationship between F_t and E_t.
3) The shore and dive counts are relative indices and their "observability" coefficient is estimated in comparison with the abundance estimates for the catch for the years 1989 and 1990 (small salmon only), which are not precisely estimated.
4) The "observability" coefficient for the redd counts is then determined by comparison with the abundance estimates from the shore and dive counts (the years 1996, 2000, 2001 and 2002) and used to estimate abundance for the years 1997, 1998 and 1999.
5) The electrofishing data spans some of the time periods of the other data sets, but has limited contrast (Figure 6). The parameters for the electrofishing components are poorly determined and, as a result, the juvenile data does not effectively link the other data series together.

We explored several alternative model formulations and data subsets while trying to alleviate this problem:

1) We attempted to estimate fishing mortality rates for the 1951 to 1963 time period. Inclusion of these data would increase the number of data points used to estimate the relationship between F_t and E_t. However, we had difficulty with the fishing effort time series (increases of 45 times between 1959 and 1960, with a 10 times increase in catch) and did not know the proportion of fishing that occurred upstream or downstream of the dam. We therefore did not include these data in the model, but have included the fishway counts for comparative purposes in this manuscript.

2) We tried to find a stronger signal in the electrofishing data by selecting subsets of these data, including:

i. all of the electrofishing data,

ii. only the electrofishing data unaffected by stocking, and
iii. each of the above with and without the 1982 data. With the exception of 1982, there is little variability in the electrofishing data. The 1982 parr densities are much higher than other years, and indicate three strong consecutive year classes.

We also tried using electrofishing data for only one or two age categories. Given the limited contrast in the data, model parameters for the electrofishing component were poorly determined irrespective of the data used. We therefore present model results with and without the electrofishing component.

3) We fixed the redd count and shore and dive count coefficients as constants ranging between 0.1 and 0.9. The abundance estimates in the 1990's and 2000's are very sensitive to this manipulation.

4) The possibility that F_t was not proportional to E_t was investigated by estimating the shape parameter b, using several data subsets and combinations of fixed and estimated parameters. Estimates for b were typically about 1.15 (s.e. = 0.21) for small salmon and 1.31 (s.e. = 0.51) for large salmon and at no time were significantly different from 1. Estimation of b created further difficulties in the MCMC simulations through its covariance with the fishery catchability coefficients. We therefore fixed b as a constant equal to 1.0 for the model runs presented here.

In the results that follow, we focus primarily on four model runs (Table 6). In Model 1, we include the electrofishing component (excluding data potentially affected by stocking) and estimate the log of total escapement in each year (39 parameters), the average proportion of the population that are small salmon (one parameter), the catchability and observability coefficients for the recreational fisheries, redd counts, shore/dive counts (four parameters), and the slope at the origin and asymptotic level for the three ages of fish in the electrofishing data (six parameters), for a total of 50 parameters. In Model 2, the electrofishing component is not included and remaining 44 parameters are estimated. In Model 3, we include the electrofishing component, fix the shore and dive count coefficient, q_{swim}, at 0.5, and estimate the remaining 49 parameters. In Model 4, we exclude the electrofishing component, fix q_{swim} at 0.5, and estimate the remaining 42 parameters. A fifth model was also examined which included only the recreational catch and effort, adult fence counts and electrofishing data for a total of 48 parameters.

The value 0.5 for q_{swim} was chosen somewhat arbitrarily based on experience in other rivers and the results of Models 1 and 2. The dive count coefficient has been estimated for three rivers in Cape Breton, NS, using mark-recapture (MR) experiments (Peter Amiro, unpublished data). In seven MR experiments in the Middle River, NS between 1994 and 2000, q_{swim} averaged 0.63 (range: 0.50 to 0.76). Similarly, in the North River, NS, q_{swim} averaged 0.46 (range: 0.36 to 0.57) based on five MR experiments between 1994 and 1998. In five MR experiments between 1994 and 1998 in the Baddeck River, NS, q_{swim} averaged 0.59 (range: 0.42 to 0.65). The grand mean of these experiments is 0.57 (sd = 0.11; n=17). In the analysis presented herein, q_{swim} was 0.32 and 0.26 when estimated using Models 1 and 2 respectively. The constant value of 0.5 for Models 3 and 4 was selected based on these observations.

Results

The fit of the predicted to observed catch for both large and small salmon is shown in Figure 10. The predicted catch roughly tracks the observed catch although some outliers are evident. Predicted catches and exploitation rates are very similar for the four models. During the 1960's and early 1970's, exploitation rates can be calculated using the adult counts at the counting fence and observed catches. The predicted exploitation rates reflect the pattern in the observed exploitation rates (Figure 10), although an outlier is evident for small salmon in 1973. The high predicted exploitation rate in 1983 is the result of a reported effort of 14,440 rod days in that year, more than twice the effort in 1982 and more than three times the effort in 1984. The maximum likelihood estimate (MLE) of the proportion of small salmon in this population, about 0.47, was similar from the four models (Table 6). The logarithms of catchability coefficients for the recreational fishery were slightly higher for Model 4 than the other models (Table 6). The Model 4 MLE's suggest that at a fishing effort of 3,000 rod days, 29.9% of the small salmon and 25.0% large salmon would be captured by the recreational fishery. Trace plots and autocorrelation plots for the MCMC chain for the catchability coefficients are not indicative of convergence problems (plots for small salmon are shown in Figure A2.1). Posterior probability densities for the log of the recreational fishery catchabilities are relatively wide (Figure 11). The 10^{th} and 90^{th} percentiles of the posterior density for the log of the catchability for small salmon are -9.31 and -8.65, implying an 80% Bayesian credible interval (BCI) for the exploitation rate at an effort of 3,000 rod days of 23.8 to 40.7%. Similarly, the 80% BCI for the exploitation rate for large salmon at an effort of 3,000 rod days is 18.2 to 37.3%. Posterior probability densities for the annual exploitation rates are provided in Appendix 1.

All four models fit the observed shore and dive counts reasonably (Figure 12), even though q_{swim} differs between models. This occurs because the abundance is changed to match the observed data, further illustrating that the data are not sufficient to "anchor" q_{swim}. Similarly, the fit to the redd count data appears reasonable for all models (Figure 12), although the estimates of q_{redd} vary between 0.29 and 0.59 (Table 6). Trace and autocorrelation plots for q_{redd} show high autocorrelation unless q_{swim} is held constant (Figure A2.2). Based on Model 4, the 80% BCI for q_{redd} is 0.39 to 1.68 (Figure 13).

Although the predicted densities of juvenile salmon track the observed densities reasonably well (Figure 14), the signal in the electrofishing data is relatively weak. The asymptotic levels (R_0) for age-0 and age-1 salmon, based on Model 1, are 67.0 and 27.0 fish per $100m^2$ respectively, and are higher than the values of 39.3 and 16.1 fish per $100m^2$ estimated for Stewiacke River salmon (Gibson and Amiro 2003). However, the wide standard deviations on the BSR estimates (Table 6) and high autocorrelation in the MCMC chains (Figure A2.3 to A2.5) indicate that these parameters are not well estimated from these data. The MLE for R_0 for age-2 fish consistently hit the upper bound placed on the parameter, suggesting that the relationship between egg deposition and the resulting density of age-2 fish is not density dependent (Figure 15). This observation is inconsistent with the density dependent relationships between egg deposition and age-0 and age-1 parr densities, further illustrating the difficulties with this component of the model. When the electrofishing

component of the model is included, the estimated mean population size for the 1977-1981 time period is about 1.7 times higher than when the electrofishing is excluded (Table 6).

Parameter estimates are also presented for a fifth model run in Table 6. During this run, the shore and dive count, and redd count components of the model were not included; only the recreational catch and effort, adult fence counts and electrofishing data were used. From this run, MLE's of the five-year mean population size for all time periods are within the range of those obtained from the other models (Table 6), although population estimates cannot be obtained for some years due to the confounding effects of stocking.

The estimates of population size prior to 1988 are not very sensitive to model selection with one exception. When the electrofishing component of the model is included, the estimated spawning escapement in 1980 and 1981 is higher than when the electrofishing component is excluded as a result of the high age-0 and age-1 parr densities recorded in 1982. Otherwise, the logarithm of the spawning escapement during the early time period typically varies by less than 0.2 among the four models (Table 6). Estimates of the number of salmon returning to the Big Salmon River from 1989 to 2002 are sensitive to model selection (Figure 16), and are determined primarily by q_{swim}. Model 1 (q_{swim} estimated and electrofishing included) produces the highest estimates of abundance during this period (Table 6), while estimates from the other models are more similar. A MLE for q_{swim} of 0.323 was obtained from Model 1, although the trace and autocorrelation plots (Figure A2.6) show that q_{swim} is not well determined in the models with or without the electrofishing data. Comparison of its traces with those for $\log(N_{1974})$ (Figure A2.7) suggest that this parameter has little influence on the abundance estimates in the earlier years. Similar comparisons for later years (e.g. 1996 (Figure A2.8)) show convergence problems with the MCMC chain for population size estimates when q_{swim} is estimated. Fixing q_{swim} at a constant value alleviates this issue.

The time series for the MLE's of the numbers of salmon returning to the river (before the recreational fishery and after the commercial fishery), shown in Figure 16, suggest the number of salmon returning to the river peaked in 1966 at 5,043 salmon (80% BCI = 3,996 to 6,686). From Model 4, the MLE's of the number of salmon returning to the river do not exceed 100 fish after 1996, and do not exceed 500 fish after 1991. Posterior probability densities for the number of salmon (size groups combined) returning annually, based on Model 4, are provided in Figures A1.1 to A1.4 and percentiles of these distributions in Table 7. An 80% BCI for the number of returning salmon in 1965 is 2,916 to 4,890 fish. In contrast, the 80% BCI for salmon returns in 2002 is 18 to 133 fish.

We estimated the decline in population size for 5, 10, 20 and 30 year time periods using all four models. To reduce the effect of large or small year classes, we estimated mean number of fish returning to the river for the five year time periods: 1967-1971, 1977-1981, 1987-1991, 1992-1996 and 1997-2001. Estimates of the mean spawning run size for the 1997-2001 time period (Table 6) ranged between 68 (Model 4) and 155 fish (Model 1). In comparison, the estimates of the mean spawning run size for the 1967-1971 time period ranged between 1982 (Model 3) and 2089 fish (Model 2).

Percent decline was calculated as the complement of the ratio of the 1997-2001 mean to the means for other time periods, converted to a percentage. Estimates for the percent decline range between 63.1 and 79.5% for the 5-year comparison, between 91.2 and 94.7% for the 10-year comparison, between 94.8 and 96.7% for the 20-year comparison and 92.2 and 96.7% for the 30-year comparison (calculated from ratios in Table 6). The posterior probability densities for the percent decline from Model 4 (Figure 17) indicate a 90% probability that the mean population size for the 1997-2001 time period has declined by more than 54.3% since the time period 1992 to 1999, and a 90% probability that the five-year mean population size has declined by more than 93.5% over the last 30 years.

Discussion

In this document, we have provided estimates of the number of fish returning to the Big Salmon River, NB, annually from 1964 to 2002, and used these results to estimate the percent decline in the population during this time period. Spawning escapements and harvest rates for the recreational fishery on this river are also provided for this time period. Overall the results suggest that the population decline is greater than 95 percent during the last 30 years.

We focused primarily on four models to assess the status of BSR salmon. Overall, the data and analyses suggest that:

1) The abundance estimates before 1988 are not very sensitive to model selection.
2) The abundance estimates after 1988 are quite sensitive to model selection.
3) Sufficient data to meaningfully estimate q_{swim} are not available.
4) The electrofishing data does not contain a strong enough signal to affect the model.

As a result, our preference is for Model 4.

While the results from the four models are similar, none of the models are entirely satisfactory. The main issue is that the data are not sufficient to provide good estimates of the probability of observing a salmon by streamside observation or by dive count because few concurrent reliable indicators are available in a dive count or streamside count year. There are only two years in which the recreational fishery (small salmon only) and the counts occurred concurrently. Inclusion of the electrofishing data did not improve the fit of the model.

Model 4 (electrofishing excluded and q_{swim} fixed at 0.5) was the only model for which Bayesian posterior distributions could be derived. A Bayesian approach to estimation attempts to incorporate uncertainty from all sources when deriving probability distributions for the parameters of interest. Treating q_{swim} as a constant ignores uncertainty in a key model parameter. The widths of the resulting posteriors are probably underestimated as a result. This issue aside, the MLE's for the percent decline from all four models are similar and suggest that the population has declined by about 97% since the late 1960's. As was the case for Stewiacke River salmon (Gibson and Amiro 2003), comparison of the 10^{th} percentiles of the posterior densities for the number of salmon returning to the Big Salmon River (Table 6)

from 1965 to 1967 with the 90th percentiles for the number of returning salmon since 1998, also suggests a decline of more than 90%.

During estimation, q_{redd} was not bounded at less than 1 to allow for the possibility that a fish might dig more than one redd, or for the possibility that redds might be misidentified. Barlaup et al. (1994) suggested that counting redds could lead to an over estimation of spawners since Atlantic salmon construct false or trial redds (White 1942) and females can dig more than one redd (Bagliniere et al. 1990; Marshall et al. 1997, de Gaudemar et al. 2000). The MLE's of q_{redd} obtained here were less than 1, although 34% of its probability density was greater than 1. The data therefore do not preclude the possibility that salmon dig more than one redd within this watershed or the possibility of redd misidentification.

The model could be improved with additional information about q_{swim}. One approach to providing this information would be to make inferences about the probability of observing fish from other rivers where dive counts are conducted. This information would be added to the model through an informative prior on q_{swim} (instead of the uninformative priors assumed here). An alternative would be to estimate annual abundances through mark-recapture experiments (or some other method). This approach would have the advantage of better anchoring q_{redd} and the electrofishing coefficients to abundance estimates as well.

The recent wild smolt estimates represent less than 25% of the average wild smolt counts observed from 1966 to 1971. Based on the analyses presented herein, adult population size has declined by about 95% during the same time period. The continued production of smolt given the low number of adult fish is suggestive that the freshwater habitat quality is sufficient to produce smolts, but not sufficient to mitigate against the factor responsible for the decline in abundance of adults.

In contrast with a similar analysis for Stewiacke River Atlantic salmon (Gibson and Amiro 2003), fits of the electrofishing component of the model for BSR salmon were not satisfactory, and as a result, we did not find the electrofishing data to be informative about spawning escapement. While the reasons for this problem are unknown, several possibilities are evident. One possibility is that the assumption that the proportion of large and small salmon was constant over years (made because data to allow the proportion to be estimated annually is unavailable) could lead to errors in the estimated egg deposition, the variable that links spawning escapement to juvenile density. Alternatively, if habitat use by juvenile salmon is density dependent, as suggested by Talbot (1993), then juvenile densities in favourable habitat may not respond to moderate changes in adult population size. If habitat use is density dependent, then inferring changes about population size from sampling a few sites may be very difficult (Talbot 1993). About 30 to 40 sites, distributed over a range of river gradients (a proxy for habitat quality), have been electrofished annually on the Stewiacke River. In the analysis presented here, we used data from 3 to 5 index sites electrofished annually on the Big Salmon River. Sample size may also explain the differences in the utility of the electrofishing data between the two studies.

The time periods selected for estimating declines (5, 10, 20 and 30 year comparisons of 5 year mean population size) were chosen to compare population size on the scale of

decades. As a result of this decision, the large population sizes in 1964 and 1965 were not included in the estimation. Had these years been used, the resulting estimated percent decline would have been even greater.

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Table 1. Recreational catch of small and large Atlantic salmon (number of fish) and effort (rod days) in the Big Salmon River, NB, 1951 to 1990. Also shown are the number of salmon returning to the river from 1954 to 1962 obtained at a fishway near head of tide and at a counting fence in 1964 to 1973. The counts of the number of fish ascending a fishway at a dam at the head of the tide may not represent complete returns to the river. The fence counts are adjusted to include recreational removals downstream of the fence (Jessop 1986). Numbers marked with an asterisk are large and small salmon combined.

Year	Recreational Fishery			Adult Counts		
	Small Salmon	Large Salmon	Effort	Type	Small Salmon	Large Salmon
1951		8*	54			
1952		7*	103			
1953		15*	119			
1954		7*	285	fishway		250*
1955		0*	32	fishway		95*
1956		76*	640	fishway		172*
1957		270*	1679	fishway		1682*
1958		161*	1535	fishway		1010*
1959		26*	890	fishway		341*
1960		238*	41317	fishway		1551*
1961		52*	12421	fishway		706*
1962		293*	13027	fishway		1767*
1963		424*	2810			
1964	93	56	3490	fence	743	1306
1965	218	303	1336	fence	2076	1727
1966	558	217	2055	fence	2850	2374
1967	645	474	2060	fence	1465	2624
1968	137	154	4227	fence	1324	1379
1969	93	436	3390	fence	423	1207
1970	231	260	2235	fence	592	1013
1971	191	75	1990	fence	510	362
1972	182	96	1812	fence	1038	477
1973	378	130	1465	fence	538	372
1974	373	106	2079			
1975	187	94	1411			
1976	664	207	2358			
1977	200	136	1870			
1978	360	228	4050			
1979	932	389	6495			
1980	5	223	2365			
1981	645	304	4735			
1982	456	328	6300			
1983	304	149	14440			
1984	351	0	4315			
1985	278	0	2971			
1986	124	0	1295			
1987	31	0	320			
1988	30	0	640			
1989	150	0	866			
1990	45	0	517			

Table 2. Counts of adult Atlantic salmon by stream-side observation and dive surveys in the Big Salmon River from 1988-2002. Data sources and spawning escapement estimates from the source documents are also provided.

Year	Date	Count technique	Count	Escapement estimate	Reference	Notes
1988	Fall	diver observations	300-400 fish	350	Amiro et. al. (1989)	
1989	Fall	diver observations	975 fish	975	O'Neil et. al (1989)	
1990	Oct. 18	diver observations	64 small / 169 large	235	Amiro et. al. (1991)	a
1991	Aug. 16	diver observations	49 small / 115 large	-	Amiro (1992)	
1991	Sept. 12/17	diver observations	105 small / 151 large	300	Amiro (1992)	b
1992	Aug. 21/Sept. 29	diver observations	150 fish	150	Amiro et. al. (1993)	
1993	Aug. 27	stream-side obs.	165 fish	300	Cutting et. al. (1994)	
1994	Sept. 27	stream-side obs.	225 fish	225	Amiro and Longard (1995)	c
1995	Aug. 22	stream-side obs.	10 small / 23 large	-	Amiro and Jefferson (1996)	d,e,h
1995	Sept. 26	stream-side obs.	18 small / 53 large	110	Amiro and Jefferson (1996)	f
1996		stream-side obs.	100-150	125	Amiro and Jefferson (1997)	
1997		stream-side obs.	50 fish	50	DFO SSR D3-12 (1998)	
1998		stream-side obs.	25-50 fish	38	Marshall et. al. (1999)	
2000	Oct. 16-18	diver observations	23 small / 5 large	41	DFO SSR D3-14 (2001)	g,h
2001	Oct. 22-23	diver observations	12 small / 8 large	30	DFO SSR D3-14 (2002)	g,h
2002	Aug. 27/Sept. 3	diver observations	16 small / 5 large	31	DFO SSR D3-14 (2003)	g,h

Notes:
- a - high water (count is a minimum estimate).
- b - complete river surveyed except one pool.
- c - diver observations on Oct. 19 indicated escapements could have been less than the 225.
- d - 15 pools surveyed representing 74% of the total river based on the 1991 complete river survey.
- e - streamside survey on Oct. 19 indicated no new fish in the river.
- f - counts were hindered by high water, estimated number is based on two partial surveys and a count for Catt and Rody pools.
- g - details can be found in Appendix 3.
- h - adjusted estimate = counts / (proportion of river surveyed) / (estimated observation rate). Amiro & Jefferson (1996).

Table 3. Summary of redds counted on the Big Salmon River by NBDNRE staff from 1996 to 2002. Sections surveyed are located in the headwaters as indicated on Figure 5.

Year	Survey Date	Section A			Section B			Number of redds observed		
		Small	Large	Total	Small	Large	Total	Small	Large	Total
1996	Nov. 6th	20	14	34	15	47	62	35	61	96
1997	Nov. 6th	3	4	7	4	11	15	7	15	22
1998	Nov. 6th	2	4	6	9	21	30	11	25	36
1999	Nov. 5th	6	2	8	18	24	42	24	26	50
2000	Nov. 7th	2	0	2	22	39	61	24	39	63
2001	Nov. 13th	4	1	5	6	26	32	10	27	37
2002	Nov. 8th	5	2	7	4	32	36	9	34	43

Section A is from the Anderson Brook pipe downstream to the Schoales Dam bridge (2.4 km).
Section B is from the old trail access point downstream to the deadwater just upstream of the King pool (2.0 km).

Notes:

- The low count in the upper section in 2000 may be a reflection of restricted access due to beaver dams. In '96/'97 an average of 33.5% of the total redds were counted in Section A, in '98/'99 the average was 16.5%, in 2000 only 3% of the total was observed in Section A.
- For the purposes of this assessment the accessible spawning area of the Big Salmon River headwaters are considered to be from the head of the deadwater at the old ford above the King Pool deadwater upstream to a point 1 km above the road pipe on Anderson Brook, excluding the deadwaters of Wilkin's Lake and Stony Lake. This section of the river encompasses 9.8 km of stream, such that the redd count survey, which covers a total of 4.4 km, provides data for 45% of the system's headwaters. The lower reaches of Manning Brook, Crow Brook, and the Walton Lake outflow are excluded. (T. Pettigrew, NBDNRE).
- The two sections represent the prime spawning areas in the Big Salmon River such that a redd/ km figure cannot simply be applied to the unsurveyed portion to provide an estimate of total redds. (T. Pettigrew, NBDNRE).

Table 4. Annual means and standard deviations (s.d.) of age-0, age-1 and age-2 Atlantic salmon densities (number per $100m^2$) in the Big Salmon River, NB, estimated during electrofishing surveys between 1968 to 2002. "N" is the number of sites electrofished in each year. Asterisks indicate years when juvenile density estimates may have been affected by juvenile stocking and may not be indicative of wild production for that life stage.

		Age-0		Age-1		Age-2	
Year	N	mean	s.d.	mean	s.d.	mean	s.d.
1968	3	16.9	19.5	14.7*	4.8	11.8	6.1
1970	4	23.6	30.7	1.2*	2.4	6.0	3.5
1971	5	6.4*	8.1	11.1	14.2	4.2*	2.9
1972	5	11.5	6.0	3.2*	3.6	4.1	4.7
1973	5	40.0	41.0	4.5*	3.0	3.0*	2.4
1982	3	68.5	70.3	47.8	30.9	10.1	6.9
1989	5	15.7	11.0	12.0	8.8	2.7	3.0
1990	5	39.3	40.2	12.0*	8.5	1.8	1.9
1991	4	17.1	14.7	14.0*	9.1	2.8*	4.2
1992	4	18.1	12.0	13.3*	8.6	1.7*	2.3
1993	3	2.3	1.4	12.5	14.3	4.4*	4.0
1994	4	10.4	11.9	6.7*	3.3	3.3	3.5
1995	4	21.8	18.4	6.4*	7.4	2.0*	1.3
1996	5	49.2	38.6	10.7	5.5	0.5*	0.6
1997	5	23.7*	19.5	6.6	10.3	1.4	0.9
1998	5	3.1	2.8	13.2*	15.5	4.4	4.7
1999	5	7.8	13.5	3.9	4.5	2.2*	3.0
2000	5	7.5	12.3	3.5	4.0	0.2	0.5
2001	5	1.6*	2.3	6.5	5.9	0.4	0.9
2002	5	16.9*	21.0	19.5*	8.3	0.6	0.7

Table 5. The statistical model used to estimate abundance of salmon in the Big Salmon River, NB.

Type of Equation	Equation	No.
Relational:	$Esc_{t,s} = Esc_t \cdot p_s$	1
	$C_{t,s} = N_{t,s}(1 - e^{-F_{t,s}})$	2
	$F_{t,s} = q_s E_t^b$	3
	$Esc_{t,s} = N_{t,s} - C_{t,s}$	4
	$Fence_{t,s} = N_{t,s}$	5
	$Redd_t = q_{redd} \sum_s Esc_{t,s}$	6
	$Swim_t = q_{swim} \sum_s Esc_{t,s}$	7
	$Eggs_t = \sum_s Esc_{t,s} fec_s$	8
	$P_{t,a} = \frac{\alpha_a Eggs_{t-a-1}}{1 + \frac{\alpha_a Eggs_{t-a-1}}{R_{0a}}}$	9
Log Likelihoods:	$\ell_{catch} = -n \ln \sigma_{catch} \sqrt{2\pi} - \sum_{t,s} C_{t,s}^{obs} - \frac{1}{2\sigma_{catch}^2} \sum_{t,s} (\ln C_{t,s}^{obs} - \ln C_{t,s})^2$	10
	$\ell_{fence} = -n \ln \sigma_{fence} \sqrt{2\pi} - \sum_{t,s} Fence_{t,s}^{obs} - \frac{1}{2\sigma_{fence}^2} \sum_{t,s} (\ln Fence_{t,s}^{obs} - \ln Fence_{t,s})^2$	11
	$\ell_{electrofishing} = -n \ln \sigma_{elect} \sqrt{2\pi} - \sum_{t,a} P_{t,a}^{obs} - \frac{1}{2\sigma_{elect}^2} \sum_{t,a} (\ln P_{t,a}^{obs} - \ln P_{t,a})^2$	12
	$\ell_{swim} = -n \ln \sigma_{swim} \sqrt{2\pi} - \sum_t Swim_t^{obs} - \frac{1}{2\sigma_{swim}^2} \sum_t (\ln Swim_t^{obs} - \ln Swim_t)^2$	13
	$\ell_{redd} = -n \ln \sigma_{redd} \sqrt{2\pi} - \sum_t Redd_t^{obs} - \frac{1}{2\sigma_{redd}^2} \sum_t (\ln Redd_t^{obs} - \ln Redd_t)^2$	14
Objective Function:	$O.F.V. = -(\lambda_1 \ell_{fence} + \lambda_2 \ell_{catch} + \lambda_3 \ell_{electrofishing} + \lambda_4 \ell_{swim} + \lambda_5 \ell_{redd})$	15

Table 6. Comparison of parameter estimates and standard deviations (in brackets) obtained from five versions of the assessment model for Big Salmon River Atlantic salmon. In Models 1 and 2, the "observability" coefficient for the shore and dive counts are estimated in the model. This parameter is held constant at 0.5 in Models 3 and 4. The electrofishing component of the model is included in Models 1 and 3, but not 2 and 4. In Model 5, only the recreational catch and electrofishing data are used.

Parameter	Year	Model				
		Model 1	Model 2	Model 3	Model 4	Model 5
Estimated Parameters:						
shore and dive count q		0.323 (0.140)	0.26 (0.225)			
redd count q		0.287 (0.175)	0.307 (0.319)	0.4 (0.196)	0.59 (0.341)	
log rec. fishing q (small)		-9.267 (0.275)	-9.118 (0.299)	-9.187 (0.264)	-9.047 (0.283)	-9.237 (0.274)
log rec. fishing q (large)		-9.556 (0.318)	-9.3 (0.338)	-9.478 (0.312)	-9.25 (0.337)	-9.519 (0.318)
log alpha (age0)		-11.659 (0.416)		-11.4 (0.325)		-11.465 (0.433)
R0 (age0)		67.007 (33.012)		57.22 (20.542)		55.358 (21.348)
log alpha (age1)		-11.842 (0.966)		-11.507 (0.648)		-11.405 (0.589)
R0 (age1)		26.993 (30.540)		22.926 (13.639)		18.649 (6.313)
log alpha (age2)		-14.331 (0.291)		-14.172 (0.247)		-14.291 (0.305)
R0 (age2)		10000 (91.833)		10000 (231.53)		10000 (169.290)
proportion small salmon		0.469 (0.0430)	0.473 (0.045)	0.469 (0.043)	0.472 (0.046)	0.469 (0.043)
Abundance Estimates:						
log(small+large escapement)	1964	7.199 (0.221)	7.122 (0.232)	7.17 (0.221)	7.095 (0.233)	7.187 (0.222)
log(small+large escapement)	1965	8.196 (0.201)	8.113 (0.211)	8.165 (0.199)	8.1 (0.211)	8.186 (0.201)
log(small+large escapement)	1966	8.377 (0.212)	8.325 (0.217)	8.357 (0.212)	8.307 (0.217)	8.369 (0.212)
log(small+large escapement)	1967	8.01 (0.213)	8.103 (0.217)	8.002 (0.21)	8.085 (0.217)	8.029 (0.210)
log(small+large escapement)	1968	7.472 (0.227)	7.382 (0.242)	7.438 (0.227)	7.351 (0.243)	7.458 (0.228)
log(small+large escapement)	1969	7.01 (0.206)	6.924 (0.231)	6.962 (0.204)	6.898 (0.231)	7.011 (0.209)
log(small+large escapement)	1970	7.216 (0.213)	7.16 (0.218)	7.194 (0.213)	7.141 (0.219)	7.207 (0.213)
log(small+large escapement)	1971	6.536 (0.202)	6.594 (0.216)	6.5 (0.203)	6.576 (0.216)	6.521 (0.204)
log(small+large escapement)	1972	7.214 (0.203)	7.079 (0.215)	7.173 (0.201)	7.063 (0.215)	7.192 (0.204)
log(small+large escapement)	1973	6.8 (0.209)	6.757 (0.212)	6.784 (0.209)	6.744 (0.212)	6.793 (0.209)
log(small+large escapement)	1974	7.672 (0.755)	7.45 (0.767)	7.586 (0.751)	7.383 (0.764)	7.636 (0.755)
log(small+large escapement)	1975	7.683 (0.752)	7.467 (0.763)	7.599 (0.749)	7.402 (0.76)	7.648 (0.752)
log(small+large escapement)	1976	8.158 (0.756)	7.932 (0.768)	8.07 (0.752)	7.864 (0.765)	8.121 (0.756)
log(small+large escapement)	1977	7.6 (0.754)	7.38 (0.765)	7.515 (0.751)	7.313 (0.763)	7.564 (0.754)
log(small+large escapement)	1978	7.286 (0.762)	7.044 (0.778)	7.192 (0.759)	6.97 (0.775)	7.247 (0.763)

Table 6 (con't)

Parameter	Year	Model				
		Model 1	Model 2	Model 3	Model 4	Model 5
log(small+large escapement)	1979	7.448 (0.773)	7.181 (0.795)	7.345 (0.77)	7.097 (0.793)	7.405 (0.774)
log(small+large escapement)	1980	7.446 (0.783)	5.522 (0.768)	7.203 (0.628)	5.454 (0.765)	7.151 (0.614)
log(small+large escapement)	1981	8.236 (0.552)	7.286 (0.783)	8.103 (0.562)	7.209 (0.78)	8.171 (0.580)
log(small+large escapement)	1982	7.044 (0.772)	6.779 (0.794)	6.942 (0.769)	6.697 (0.791)	7.002 (0.773)
log(small+large escapement)	1983	5.233 (0.819)	4.873 (0.869)	5.095 (0.818)	4.755 (0.869)	5.176 (0.822)
log(small+large escapement)	1984	7.305 (1.046)	7.112 (1.059)	7.207 (1.043)	7.024 (1.054)	7.268 (1.047)
log(small+large escapement)	1985	7.512 (1.041)	7.33 (1.051)	7.42 (1.038)	7.249 (1.047)	7.477 (1.041)
log(small+large escapement)	1986	7.206 (0.560)	7.449 (1.043)	7.066 (0.543)	7.375 (1.039)	7.168 (0.564)
log(small+large escapement)	1987	7.675 (1.032)	7.515 (1.039)	7.595 (1.029)	7.445 (1.034)	7.644 (1.032)
log(small+large escapement)	1988	6.578 (0.468)	6.988 (0.865)	6.368 (0.437)	6.625 (0.72)	6.408 (0.518)
log(small+large escapement)	1989	8.054 (0.619)	8.148 (0.866)	7.898 (0.607)	7.784 (0.72)	8.164 (0.849)
log(small+large escapement)	1990	6.697 (0.472)	7.098 (0.865)	6.492 (0.446)	6.735 (0.72)	6.647 (0.539)
log(small+large escapement)	1991	6.827 (0.397)	6.893 (1.322)	6.643 (0.377)	6.238 (1)	6.833 (0.468)
log(small+large escapement)	1992	4.472 (0.506)	6.358 (1.322)	4.201 (0.431)	5.704 (1)	4.084 (0.545)
log(small+large escapement)	1993	5.794 (0.440)	6.453 (1.322)	5.561 (0.38)	5.799 (1)	5.622 (0.468)
log(small+large escapement)	1994	5.991 (0.683)	6.764 (1.322)	5.629 (0.681)	6.109 (1)	5.569 (1.229)
log(small+large escapement)	1995	6.833 (0.750)	5.61 (1.322)	6.61 (0.65)	4.956 (1)	7.416 (0.680)
log(small+large escapement)	1996	5.886 (0.845)	5.961 (1.154)	5.5 (0.749)	5.307 (0.764)	
log(small+large escapement)	1997	4.76 (0.545)	4.766 (1.155)	4.485 (0.395)	4.112 (0.764)	4.527 (0.463)
log(small+large escapement)	1998	5.222 (0.489)	4.875 (1.155)	4.959 (0.368)	4.22 (0.764)	5.082 (0.449)
log(small+large escapement)	1999	5.513 (0.507)	5.093 (1.445)	5.263 (0.389)	4.438 (1.157)	5.339 (0.449)
log(small+large escapement)	2000	4.926 (0.846)	5.001 (1.155)	4.54 (0.749)	4.347 (0.764)	
log(small+large escapement)	2001	4.491 (0.846)	4.566 (1.155)	4.105 (0.75)	3.912 (0.765)	
log(small+large escapement)	2002	4.59 (0.846)	4.666 (1.155)	4.205 (0.75)	4.012 (0.765)	
Derived Parameters:						
a) mean N (1997 - 2001)		155.4 (72.03)	131.2 (132.03)	115.7 (35.68)	68.198 (35.05)	153.9 (143.4)
b) mean N (1992 - 1996)		420.66 (194.77)	547.78 (539.02)	318.52 (122.83)	284.74 (133.46)	452.17 (3560.1)
c) mean N (1987 - 1991)		1589.2 (668.24)	1766.7 (1075.50)	1374.4 (566.44)	1285.3 (569.48)	1624 (811.23)
d) mean N (1977 - 1981)		2988.8 (1039.30)	1767.6 (718.28)	2705.1 (900.60)	1685.2 (676.66)	2788.3 (965.55)
e) mean N (1967 - 1971)		1992.3 (204.70)	2088.7 (218.57)	1981.8 (202.47)	2079.6 (217.31)	2010.1 (205.57)
ratio: a/b		0.369 (0.20)	0.24 (0.16)	0.363 (0.17)	0.24 (0.16)	0.205 (11.22)
ratio: a/c		0.098 (0.05)	0.074 (0.06)	0.084 (0.04)	0.053 (0.04)	0.057 (3.09)
ratio: a/d		0.052 (0.02)	0.074 (0.08)	0.043 (0.02)	0.04 (0.03)	0.033 (1.80)
ratio: a/e		0.078 (0.04)	0.063 (0.06)	0.058 (0.02)	0.033 (0.02)	0.046 (2.50)

Table 7. Percentiles of the posterior probability densities for the number of Atlantic salmon returning to the Big Salmon River, NB, from 1964 to 2002. Model 4 (no electrofishing data and fixed shore and dive count q) was used to generate the probability distributions.

	Percentile								
Year	10%	20%	30%	40%	50%	60%	70%	80%	90%
1964	1,328	1,472	1,566	1,666	1,756	1,832	1,932	2,080	2,241
1965	2,916	3,206	3,410	3,590	3,760	3,929	4,166	4,430	4,890
1966	3,996	4,331	4,572	4,826	5,103	5,364	5,655	6,075	6,686
1967	3,136	3,406	3,627	3,846	4,022	4,230	4,447	4,789	5,195
1968	1,892	2,062	2,202	2,336	2,438	2,563	2,717	2,913	3,206
1969	1,082	1,196	1,267	1,338	1,416	1,490	1,586	1,674	1,837
1970	1,220	1,327	1,434	1,512	1,582	1,665	1,762	1,894	2,081
1971	688	748	792	835	883	937	994	1,059	1,164
1972	1,099	1,195	1,269	1,336	1,405	1,487	1,567	1,676	1,847
1973	758	834	896	941	991	1,046	1,109	1,183	1,295
1974	707	976	1,215	1,484	1,853	2,204	2,661	3,280	4,618
1975	689	992	1,219	1,508	1,802	2,134	2,651	3,462	4,506
1976	1,295	1,711	2,081	2,521	3,019	3,638	4,366	5,196	6,531
1977	655	888	1,122	1,405	1,687	2,013	2,496	3,168	4,178
1978	575	823	1,084	1,324	1,582	1,871	2,278	2,905	3,958
1979	879	1,305	1,616	1,960	2,320	2,730	3,363	4,092	5,688
1980	117	157	192	247	305	359	439	552	800
1981	835	1,199	1,464	1,793	2,125	2,421	3,037	3,828	5,284
1982	622	879	1,110	1,369	1,672	1,956	2,348	3,083	4,218
1983	210	296	375	460	556	671	824	1,025	1,377
1984	381	603	797	1,036	1,336	1,707	2,178	2,973	4,485
1985	440	672	899	1,207	1,527	1,989	2,579	3,334	4,810
1986	378	587	833	1,141	1,508	1,925	2,475	3,298	4,661
1987	413	683	934	1,152	1,498	1,957	2,661	3,534	4,970
1988	305	415	514	627	749	934	1,148	1,400	1,884
1989	976	1,270	1,604	1,965	2,290	2,747	3,265	3,915	5,058
1990	348	459	564	683	821	1,002	1,222	1,535	2,094
1991	147	222	311	399	507	657	872	1,199	1,993
1992	81	121	180	228	299	392	499	719	1,170
1993	96	146	198	264	338	431	555	728	1,132
1994	119	182	270	347	458	575	747	1,080	1,670
1995	38	57	79	106	137	172	227	308	502
1996	60	87	115	139	169	200	242	310	430
1997	18	26	35	43	52	62	77	98	134
1998	21	31	39	47	58	70	85	102	148
1999	14	23	33	45	63	85	119	160	265
2000	26	35	46	55	65	77	95	125	172
2001	17	24	31	36	44	53	64	83	110
2002	18	25	31	40	49	59	71	95	133

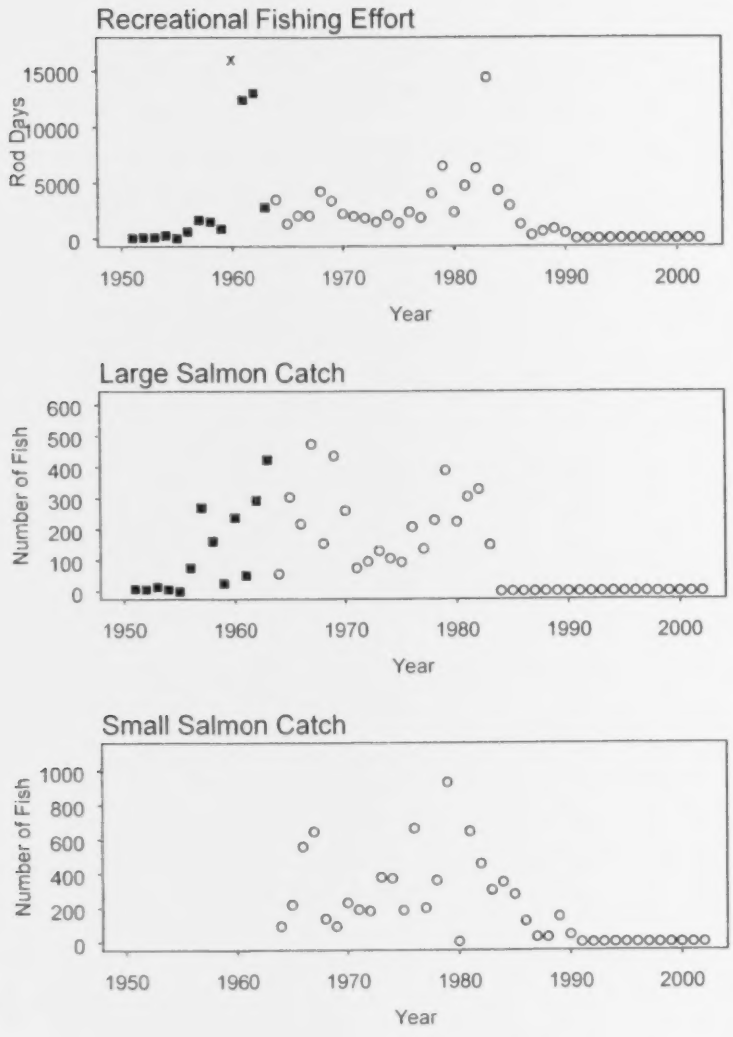

Figure 1. Recorded recreational fishing effort, and catch of large and small salmon on the Big Salmon River, NB. The squares mark a period when large and small salmon were not distinguished in the catch. All salmon were reported as "large" in O'Neil and Swetnam (1991). The "x" in effort panel is a recorded effort of 41,317 rod days in 1960.

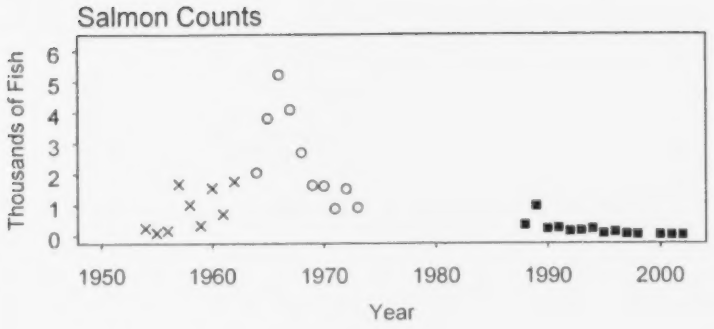

Figure 2. Atlantic salmon counts on the Big Salmon River, NB. Open circles indicate years when the count was made at a counting fence. These values are adjusted for the number of fish taken in the recreational fishery downstream of the fence and are therefore estimates of the number of fish returning to the river to spawn in the given year (Jessop 1986). X's indicate counts at a fish ladder bypassing a dam at the head of the tide (Jessop 1986). The dark squares indicate counts made by streamside observation and dive surveys and are an index of spawner escapement (recreational fisheries on this river were closed after 1990).

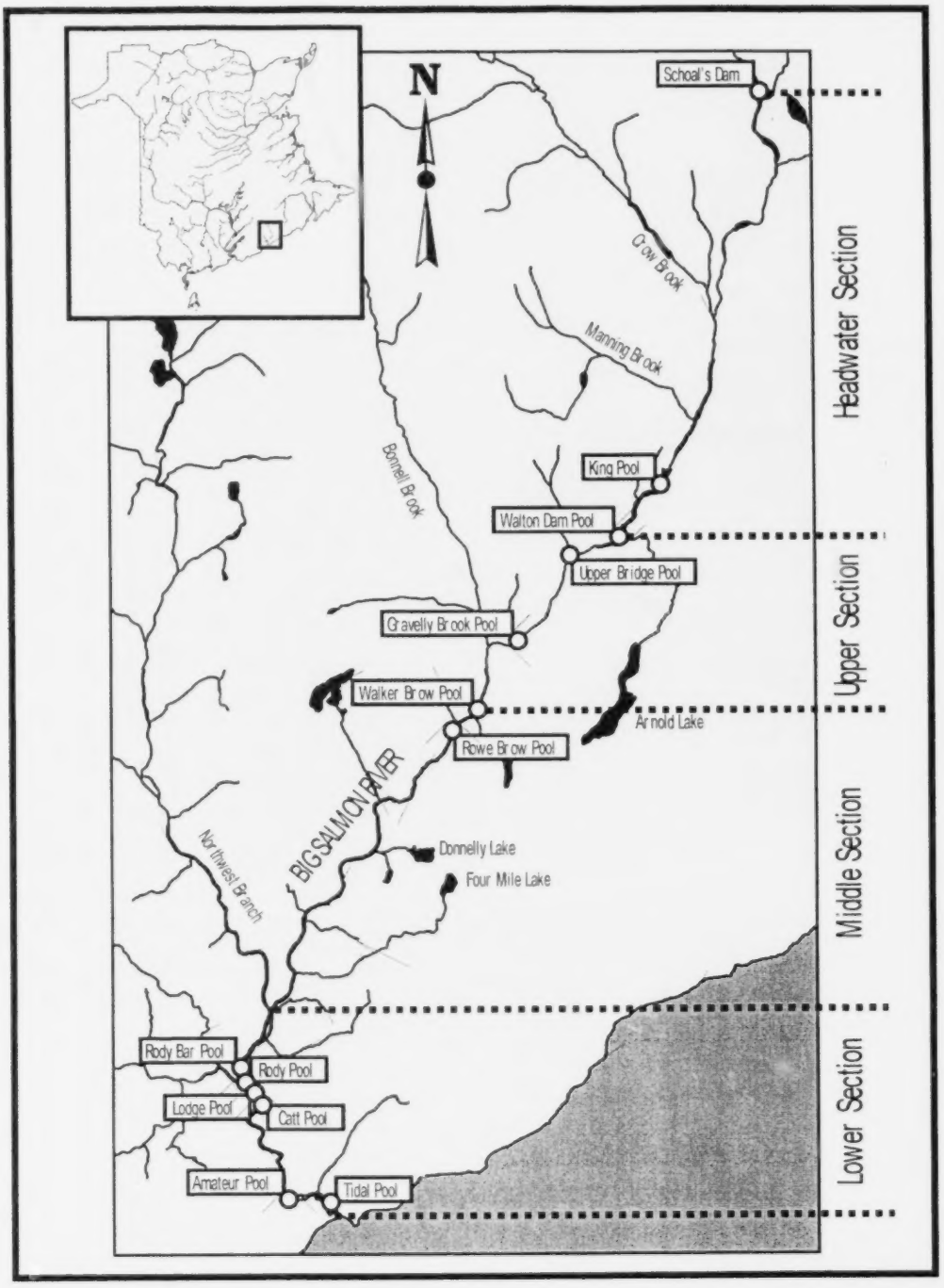

Figure 3. Location of pools and sections of the river mentioned in the text where sampling for adults and smolts was conducted in the Big Salmon River, from 2000 to 2002.

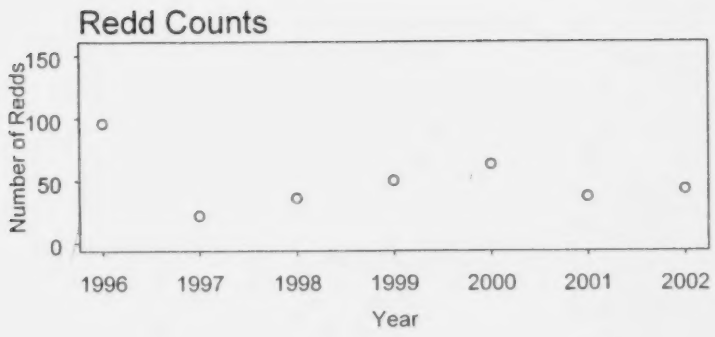

Figure 4. Redd counts on the Big Salmon River, NB from 1996 to 2002.

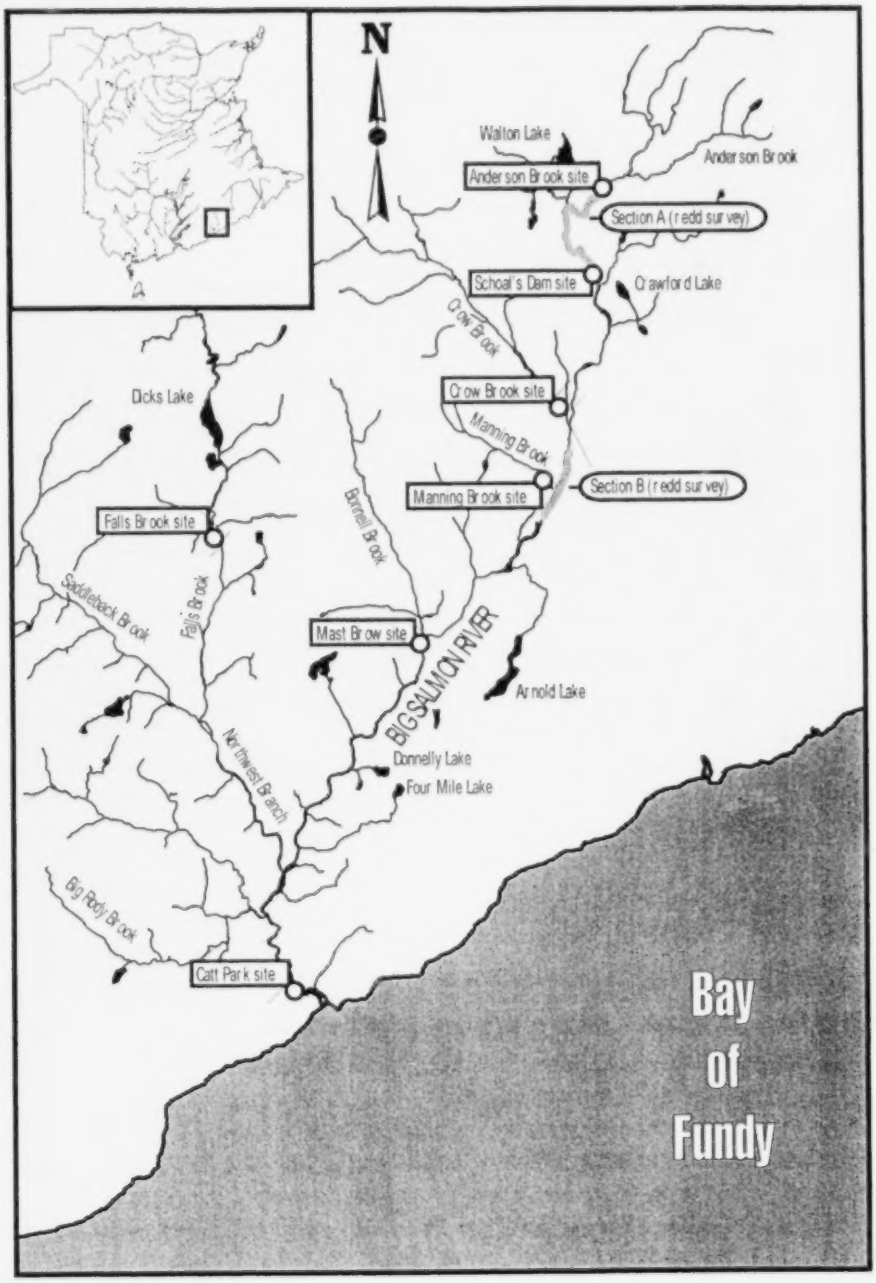

Figure 5. Map of showing the locations of areas surveyed for redds (1996 - 2002), and the location of seven electrofishing sites in the Big Salmon River, NB. Data from the Catt Park, Mast Brow, Anderson Brook, Crow Brook and Schoal's Dam sites were used in the analysis presented herein.

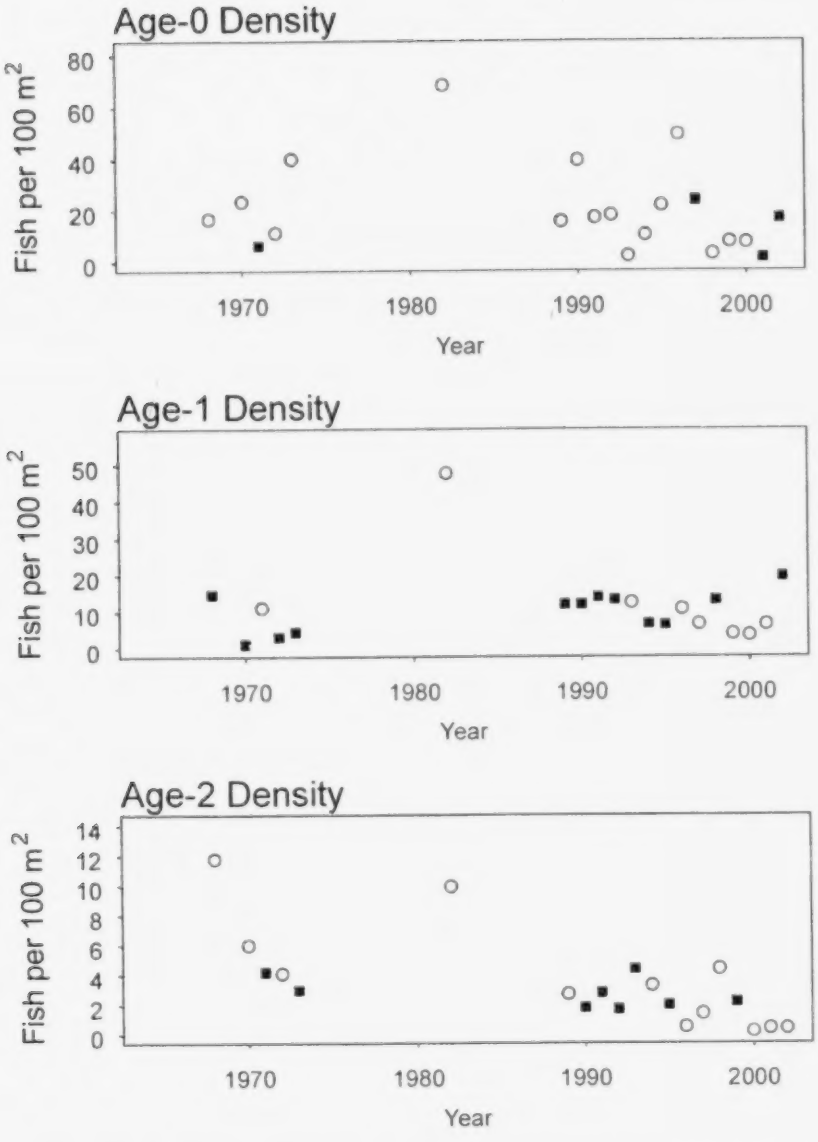

Figure 6. Mean density (fish per 100 m^2) of juvenile Atlantic salmon in the Big Salmon River, NB, determined by electrofishing at the five index sites. Solid squares indicate years where the densities may not be indicative of wild production due to the release of captive-reared fish.

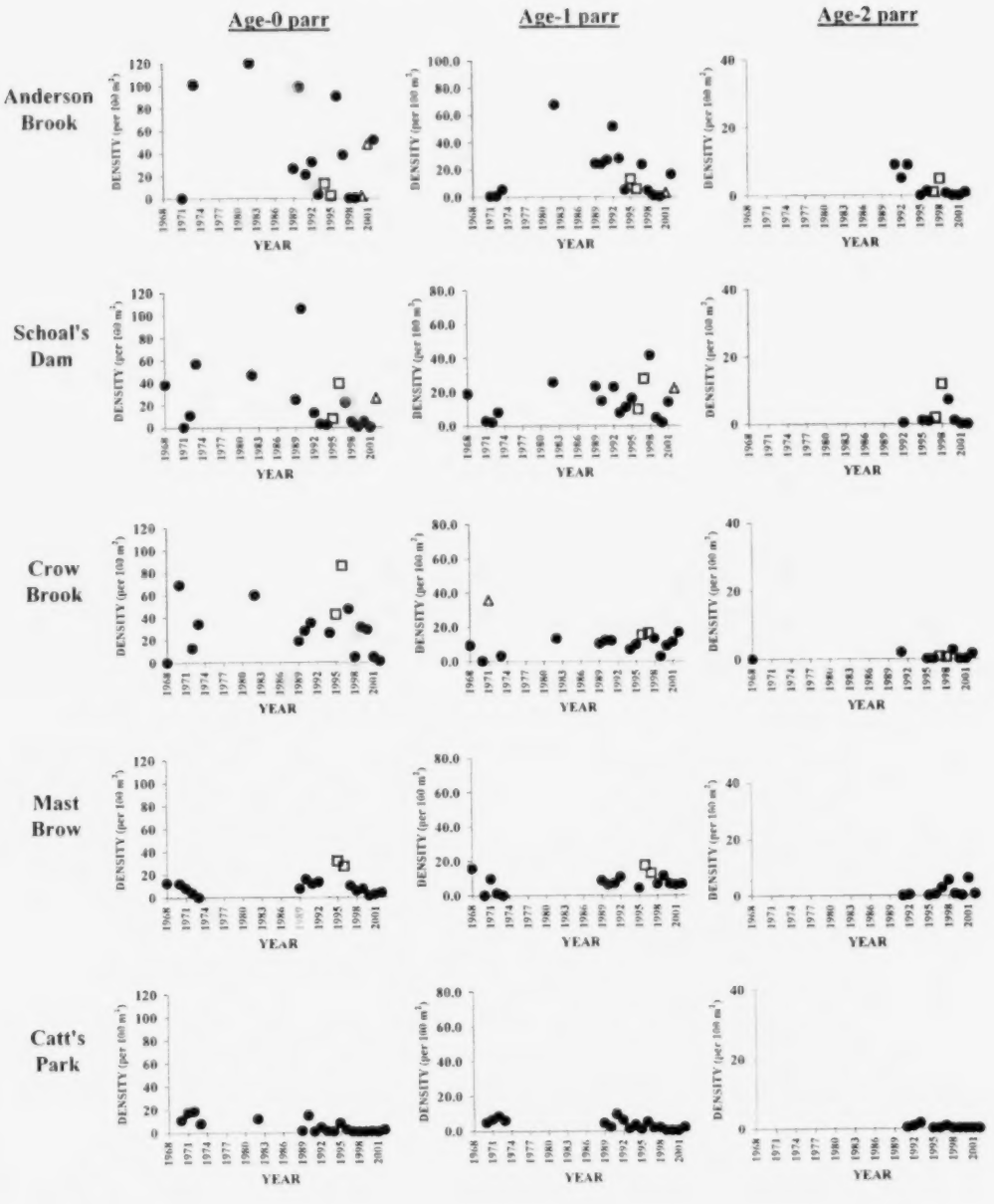

Figure 7. Age-0, age-1, and age-2 parr densities (fish per 100 m^2) determined by electrofishing at 5 sites on the Big Salmon River, NB. Densities with open squares (□) were potentially influenced by the release of cage-reared adults and those with open triangles (Δ) may have been influenced by the release of captive-reared parr in the proximity of the site prior to electrofishing during that year.

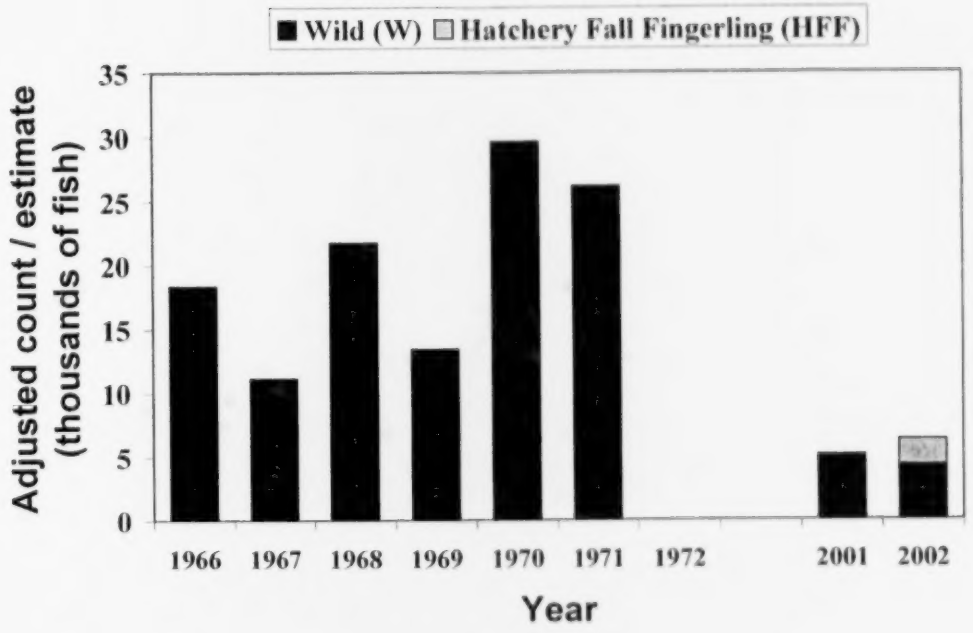

Figure 8. Adjusted counts (1966-71) and mark-recapture estimates (2001-2002) of wild and captive-reared (stocked as fall parr) smolt emigrating from the Big Salmon River, N.B. A proportion of the wild smolt captured from 1967-69 may have been unmarked captive reared fish released into the Big Salmon River from 1966 to 1967.

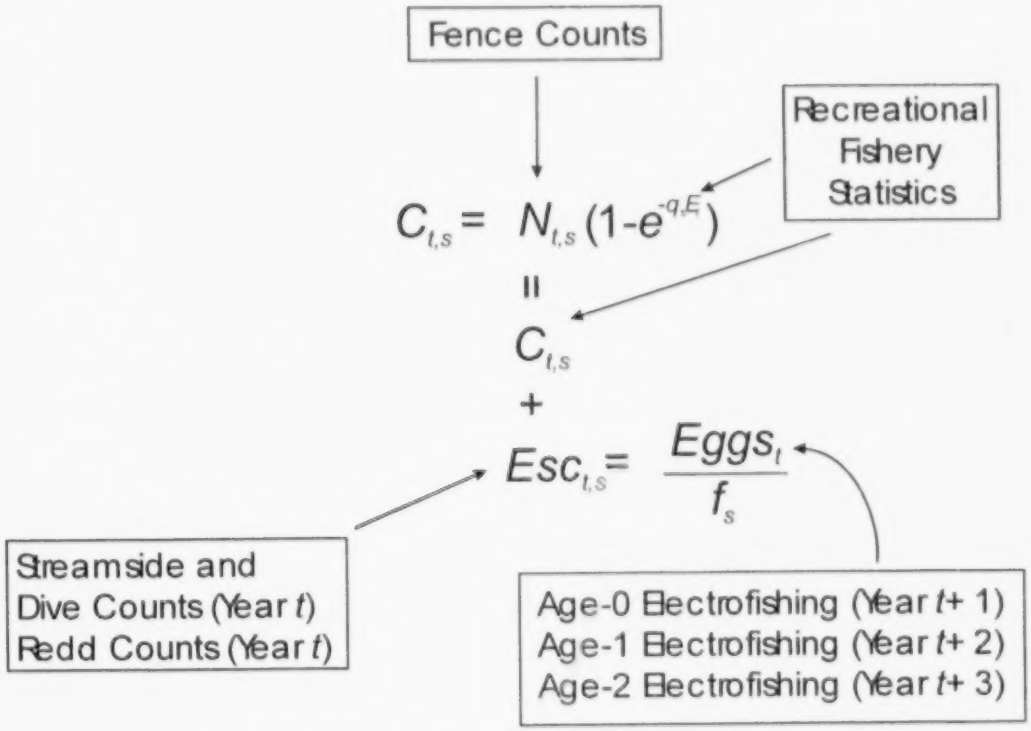

Figure 9. Schematic of model used to estimate abundance of Atlantic salmon in the Big Salmon River, NB. Data are shown in boxes and are used as indices of variables identified with the arrows. Notation and further model details are provided in the text.

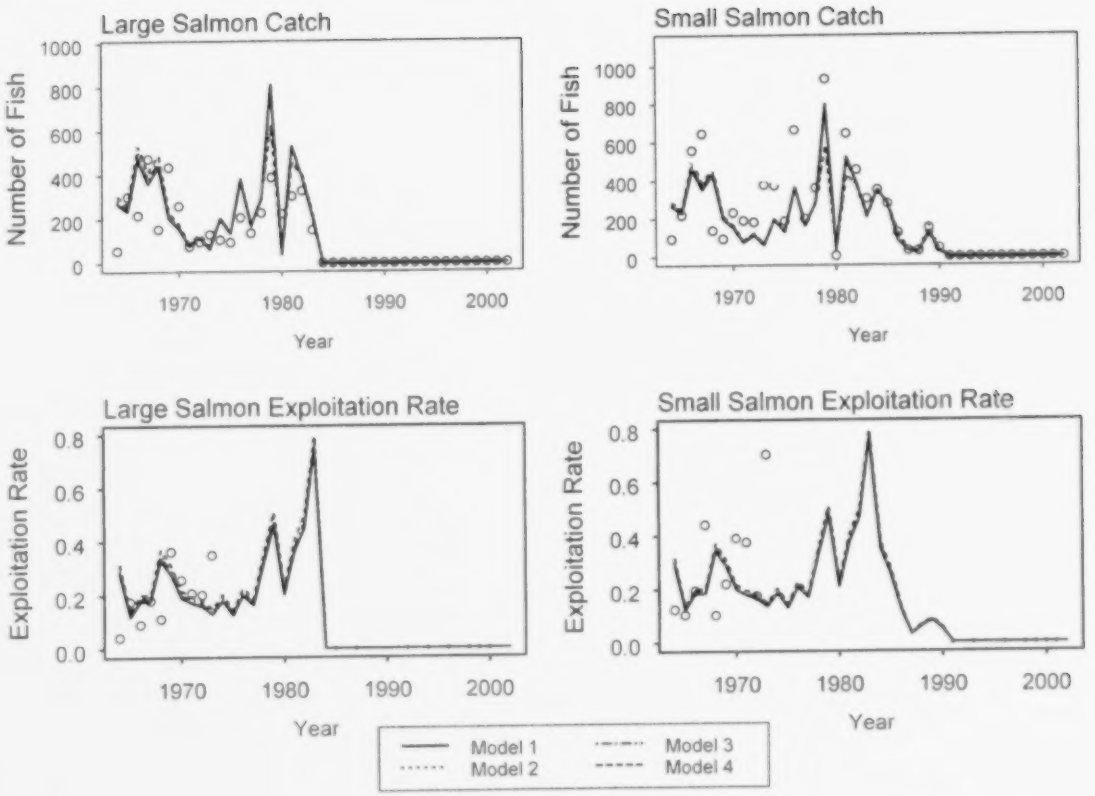

Figure 10. Estimated (lines) and observed (points) catches and exploitation rates for Atlantic salmon in Big Salmon River, NB, from 1964 to 2002. Four models are described in text.

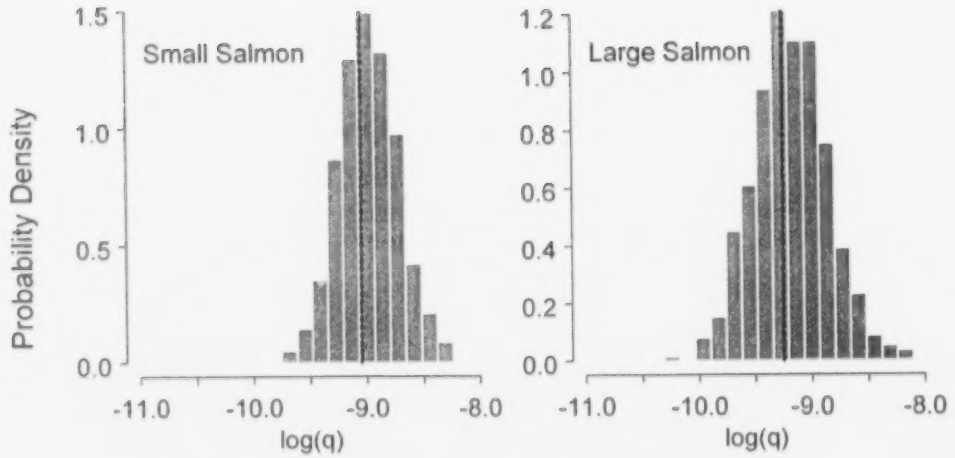

Figure 11. Posterior probability densities for the natural logarithms of the recreational fishery catchability coefficients for small and large salmon. The dashed lines show the maximum likelihood estimates.

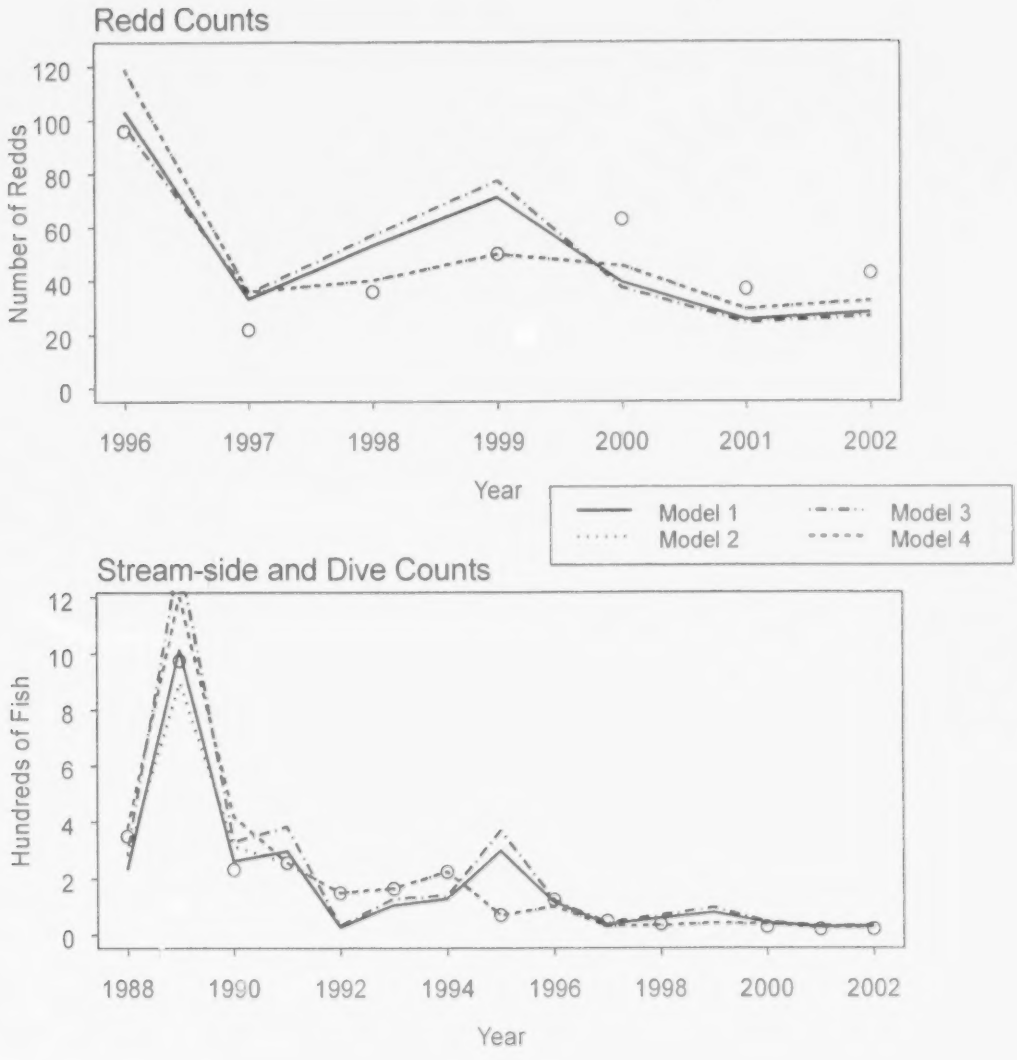

Figure 12. Estimated (lines) and observed (points) counts of salmon redds and number of Atlantic salmon observed by dive and streamside observation in the Big Salmon River, NB, from 1988 to 2002. The four models are described in text. Note that the time scales on the two graphs are different.

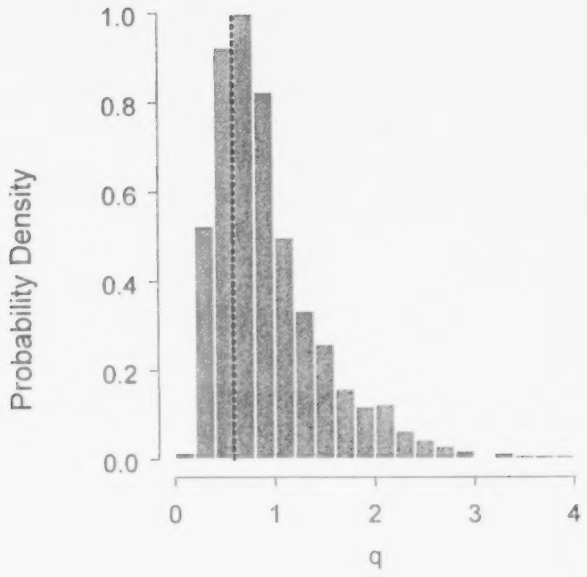

Figure 13. Posterior probability density for the redd count "observability" coefficient, q_{redd}. The dashed line shows the maximum likelihood estimate.

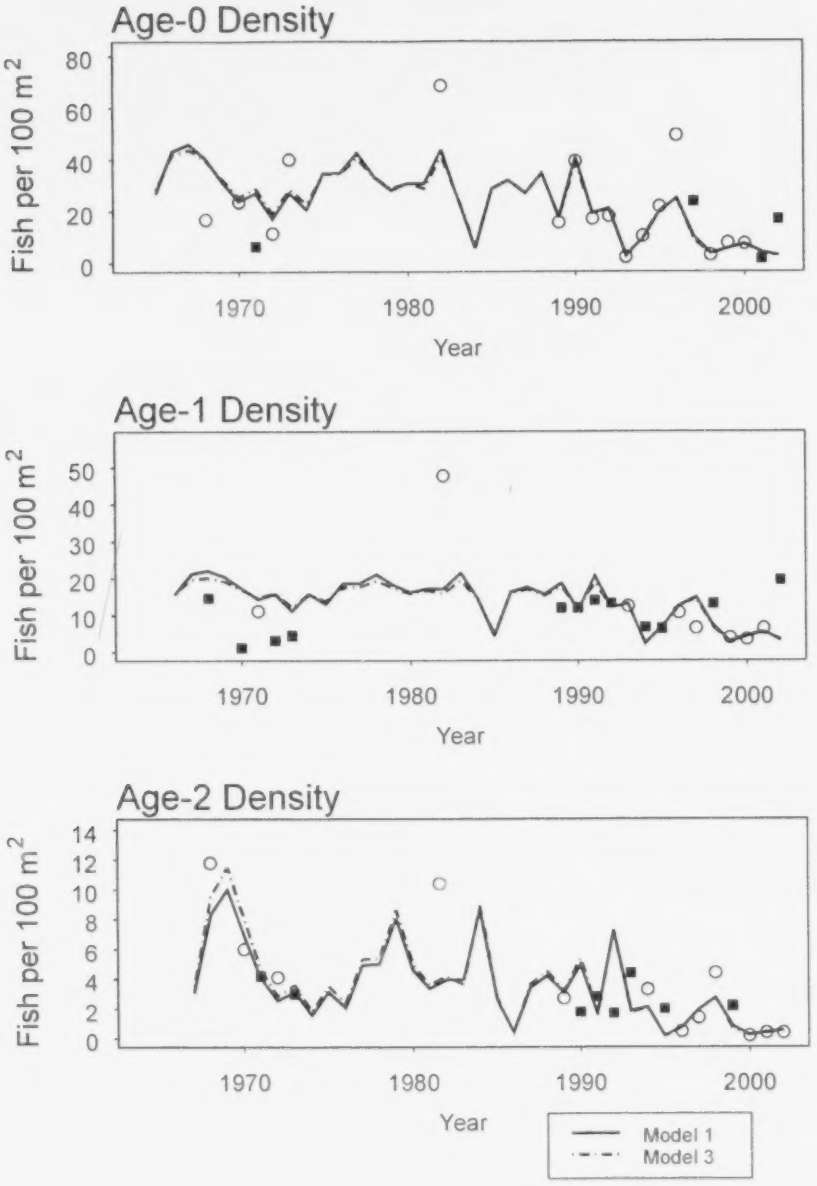

Figure 14. Estimated (lines) and observed (points) mean densities of age-0, age-1 and age-2 Atlantic salmon in the Big Salmon River, NB, from 1964 to 2002. The two model formulations are described in text.

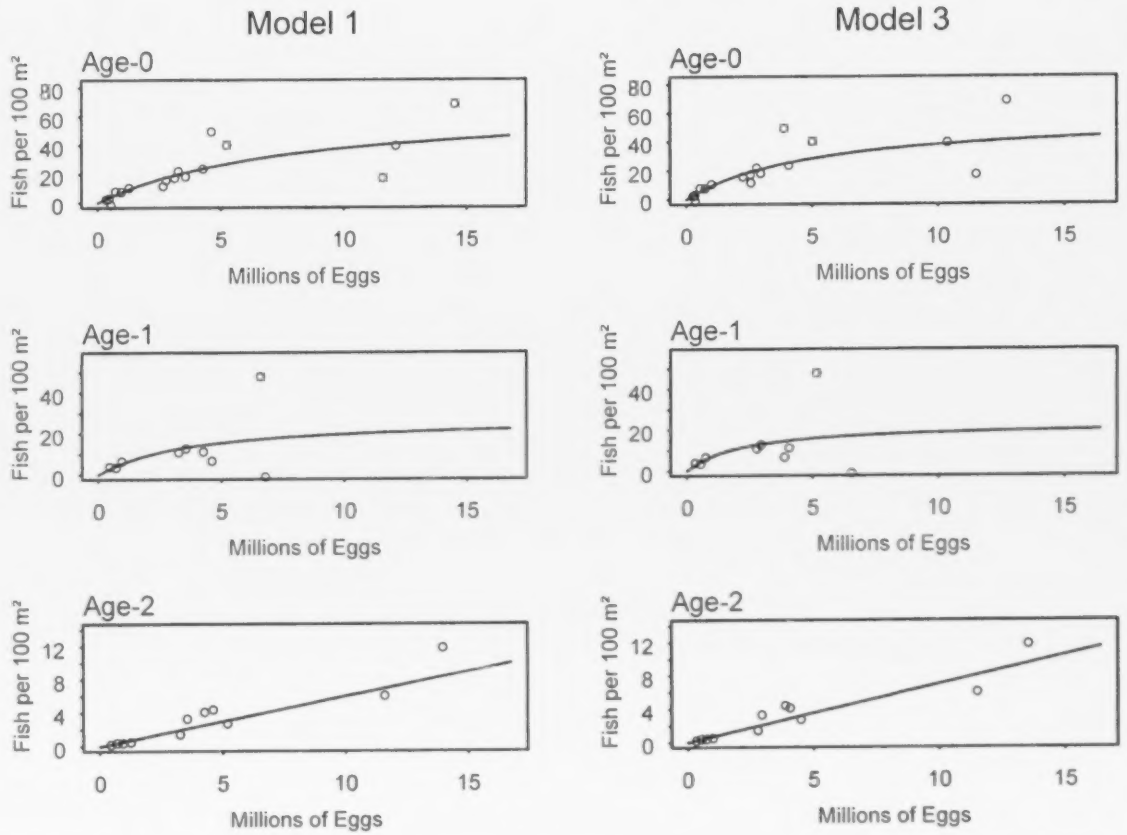

Figure 15. The relationship between egg deposition and mean densities of age-0, age-1 and age-2 Atlantic salmon in the Big Salmon River, NB. The two models used to fit the relationship are described in the text.

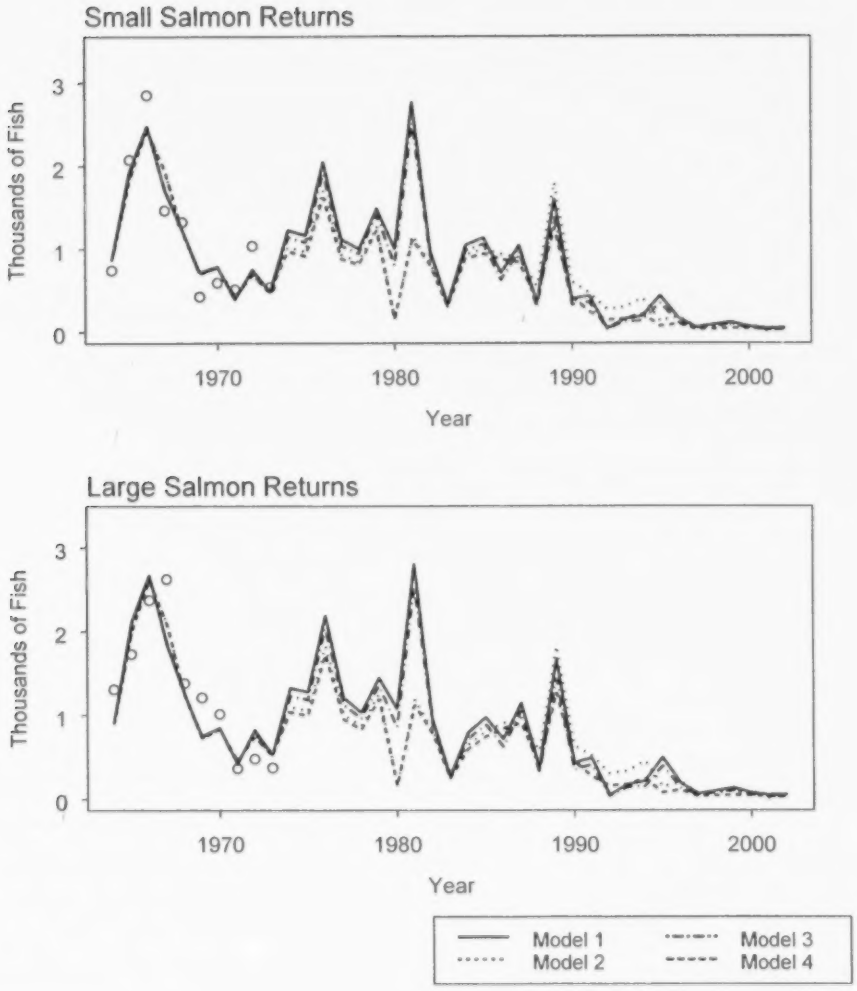

Figure 16. Estimated (lines) and observed (points) number of Atlantic salmon returning to the Big Salmon River, NB, from 1964 to 2002. The four models are described in text.

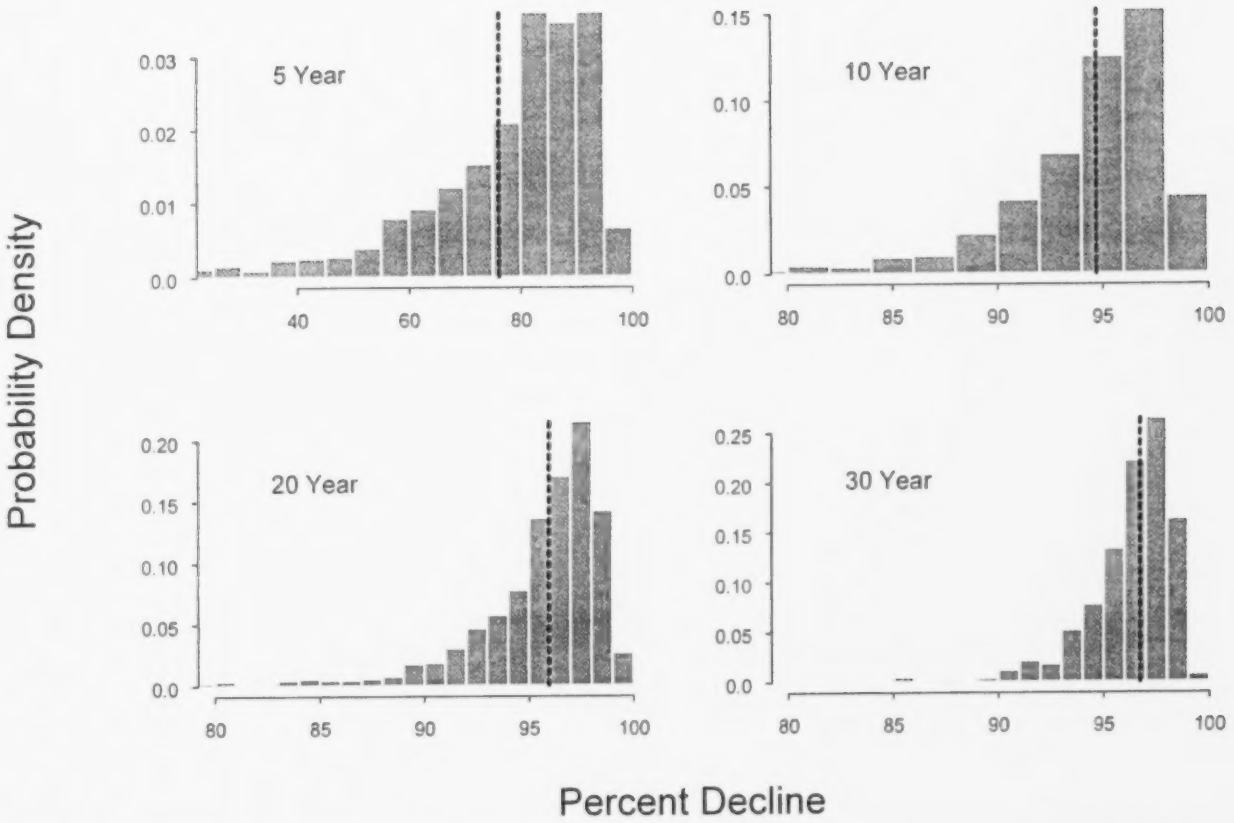

Figure 17. Posterior probability densities for the percent decline in the number of Atlantic salmon returning to the Big Salmon River over a 5, 10, 20 and 30 year time period based on Model 4 estimates of abundance. Percent decline was calculated by comparing the mean number of returning salmon for the 1997 - 2001 time period to means for the 1992 - 1996 time period (5 year comparison), the 1987 - 1991 time period (10 year comparison), the 1977 - 1981 time period (20 year comparison) and the 1967 - 1971 time period (30 year comparison). The dashed lines show the maximum likelihood estimates for the percent decline.

Appendix 1. Marginal probability densities for the number of Atlantic salmon returning to the Big Salmon River annually from 1964 to 2002 and the annual recreational catch rates for large and small salmon. The dashed lines show the maximum likelihood estimates.

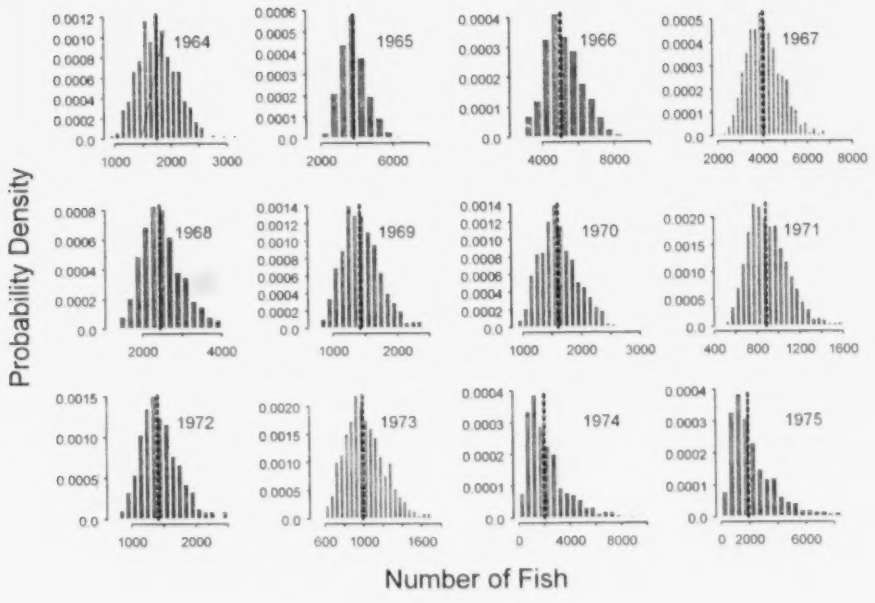

Figure A1.1. Number of salmon returning to the Big Salmon River 1964 to 1975.

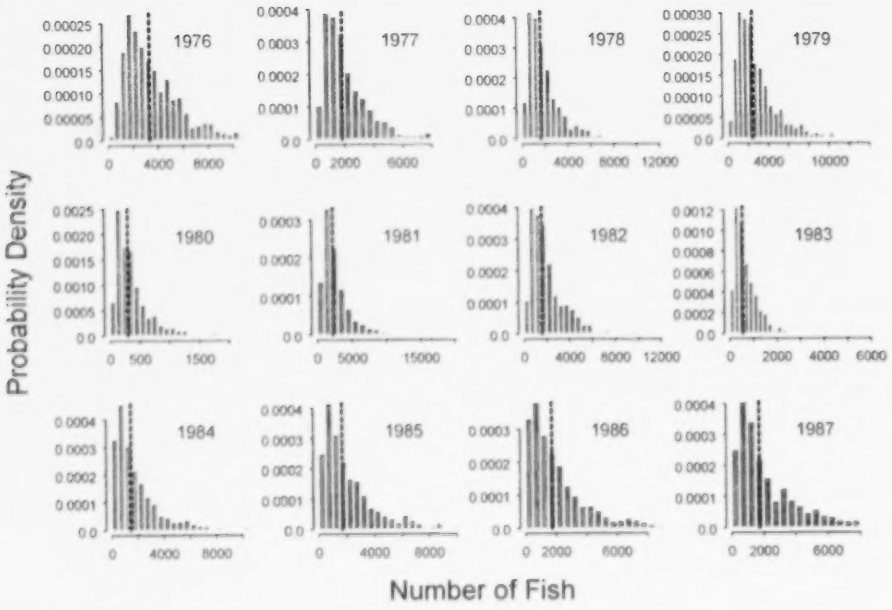

Figure A1.2. Number of salmon returning to the Big Salmon River 1976 to 1987.

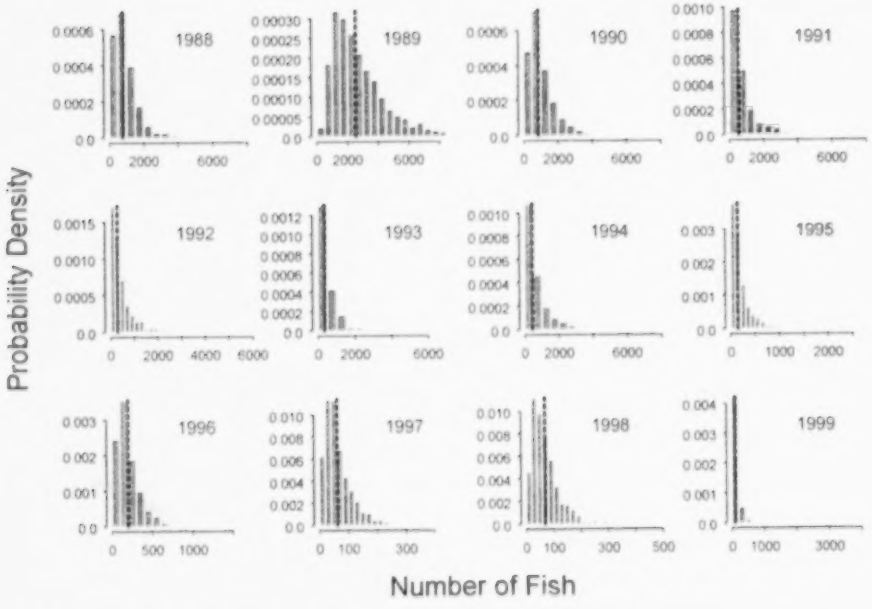

Figure A1.3. Number of salmon returning to the Big Salmon River 1988 to 1999.

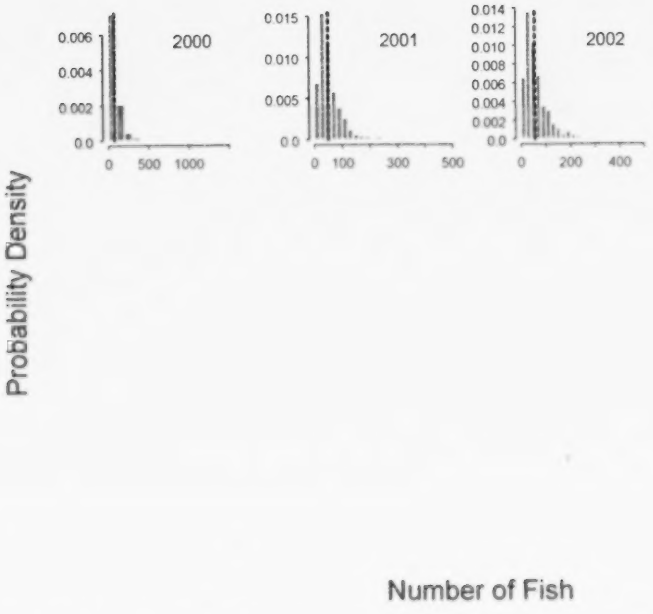

Figure A1.4. Number of salmon returning to the Big Salmon River 2000 to 2002.

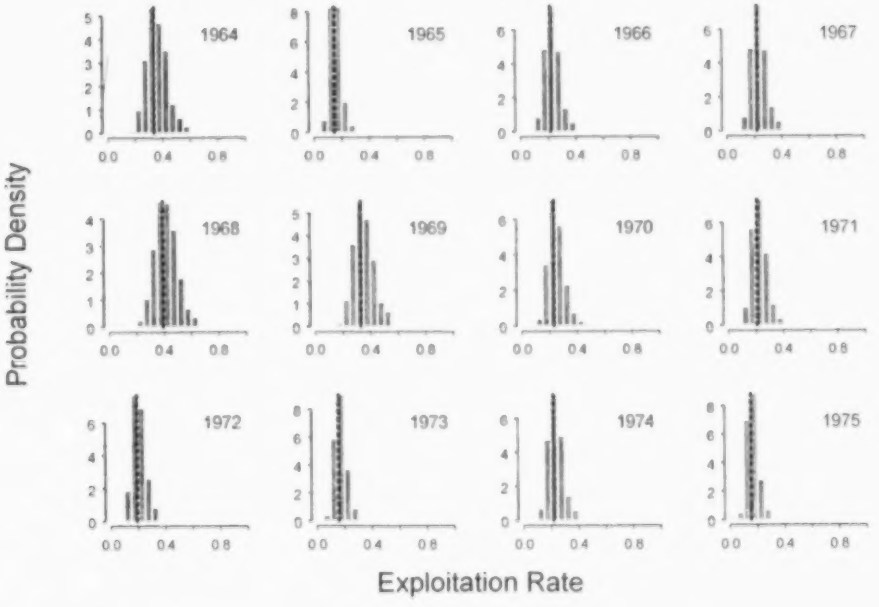

Figure A1.5. Recreational catch rates for small salmon 1964 to 1975.

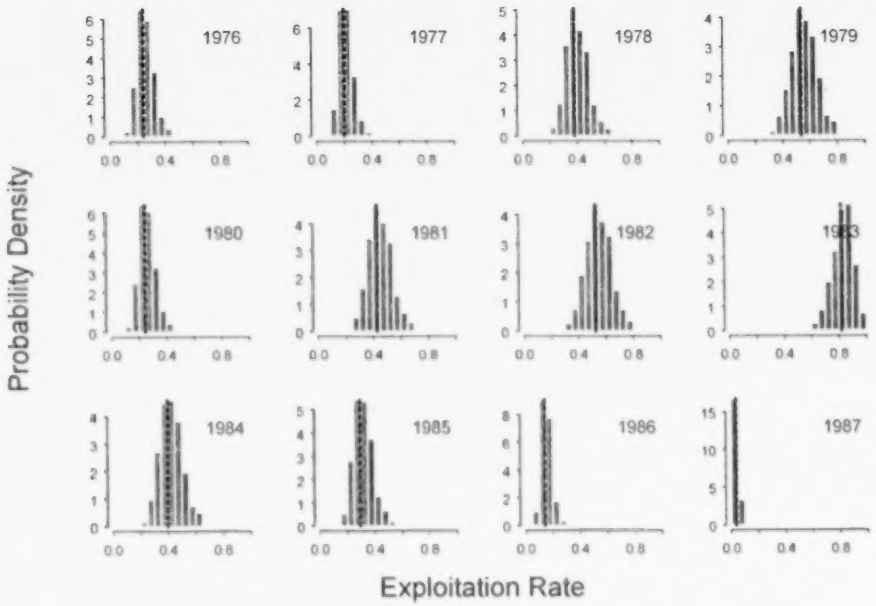

Figure A1.6. Recreational catch rates for small salmon 1976 to 1987.

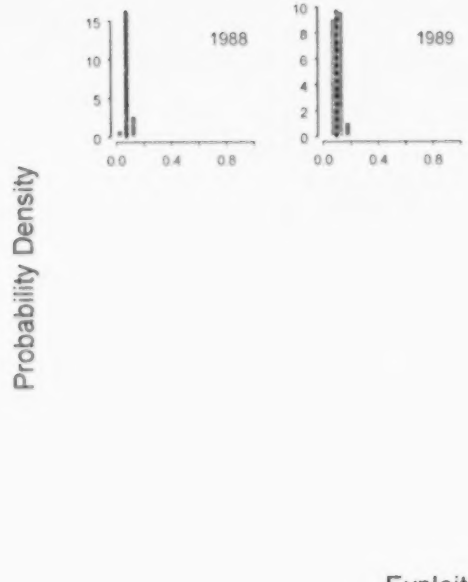

Figure A1.7. Recreational catch rates for small salmon 1988 to 1989.

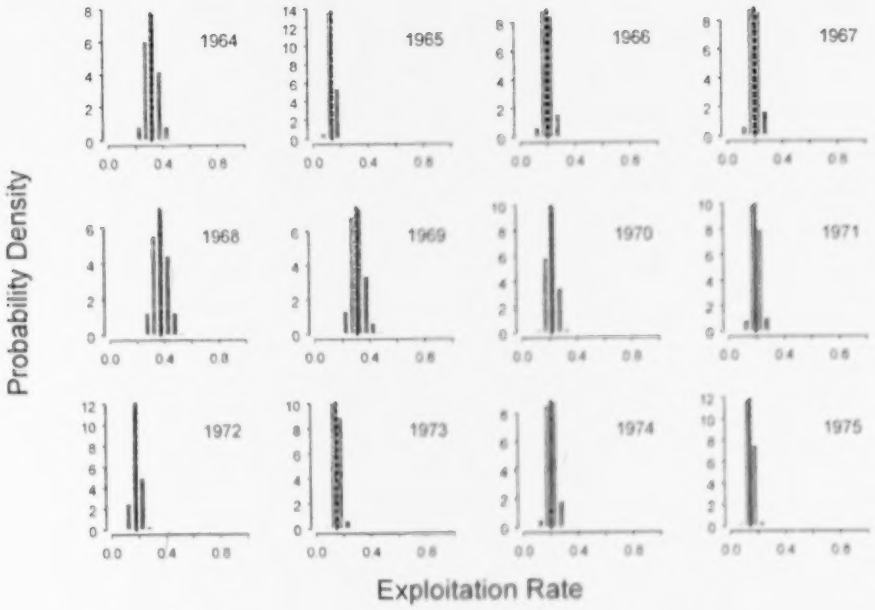

Figure A1.8. Recreational catch rates for large salmon 1964 to 1975.

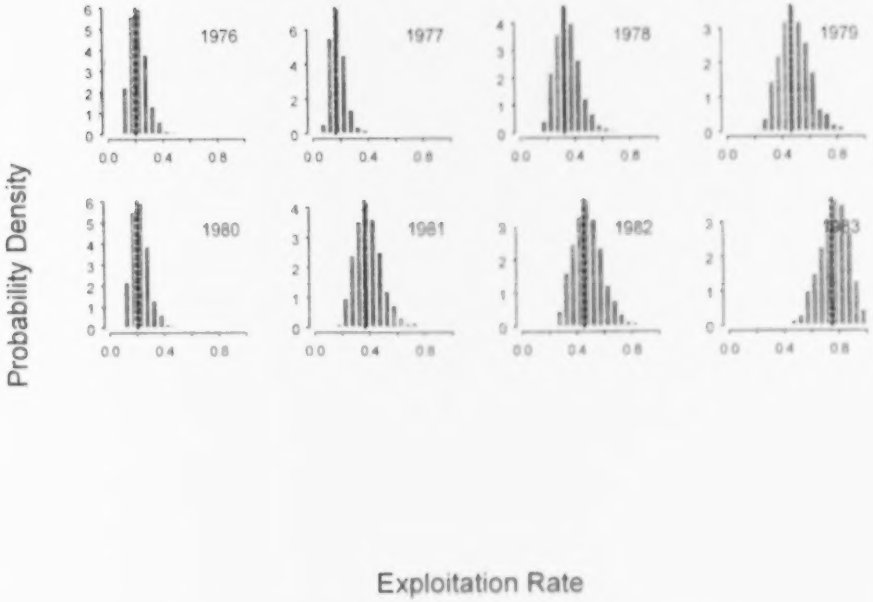

Figure A1.9. Recreational catch rates for large salmon 1976 to 1983.

Appendix 2. Trace and autocorrelation plots for the MCMC simulations for selected parameters from the 4 models.

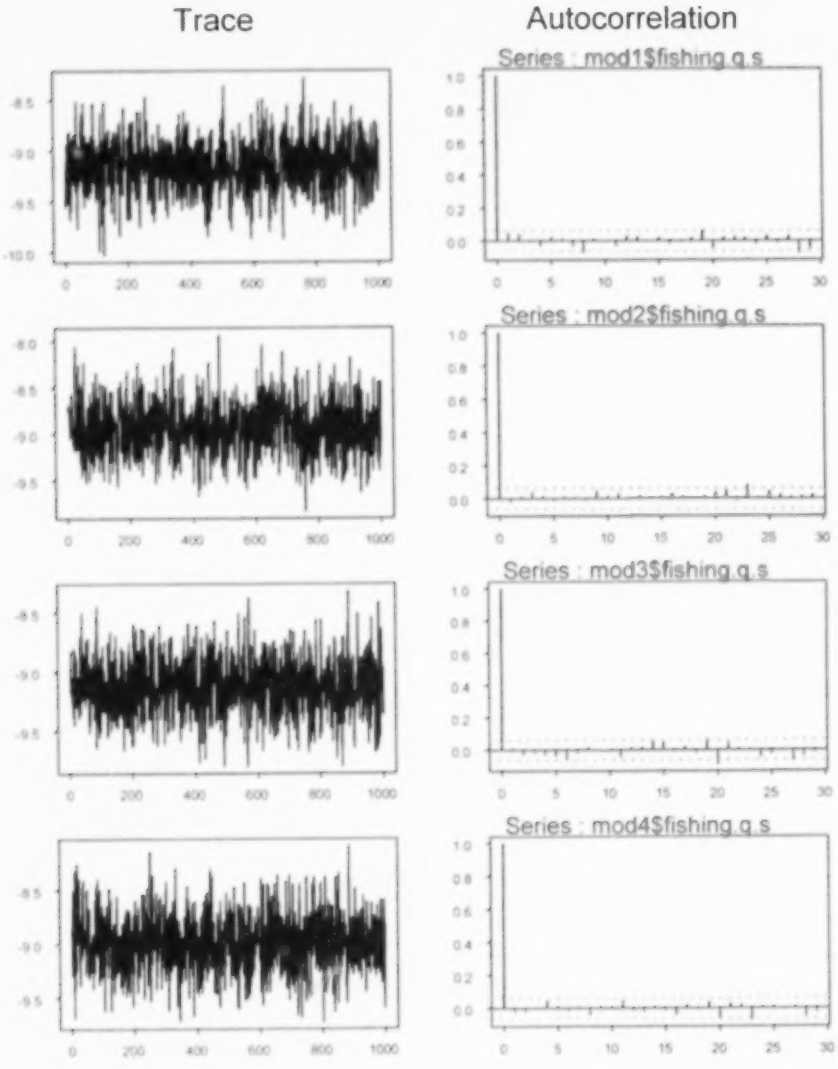

Figure A2.1. Trace and autocorrelation plots for the fishing catchability coefficient for small salmon from Models 1 (top) to 4 (bottom). Model formulations are described in text.

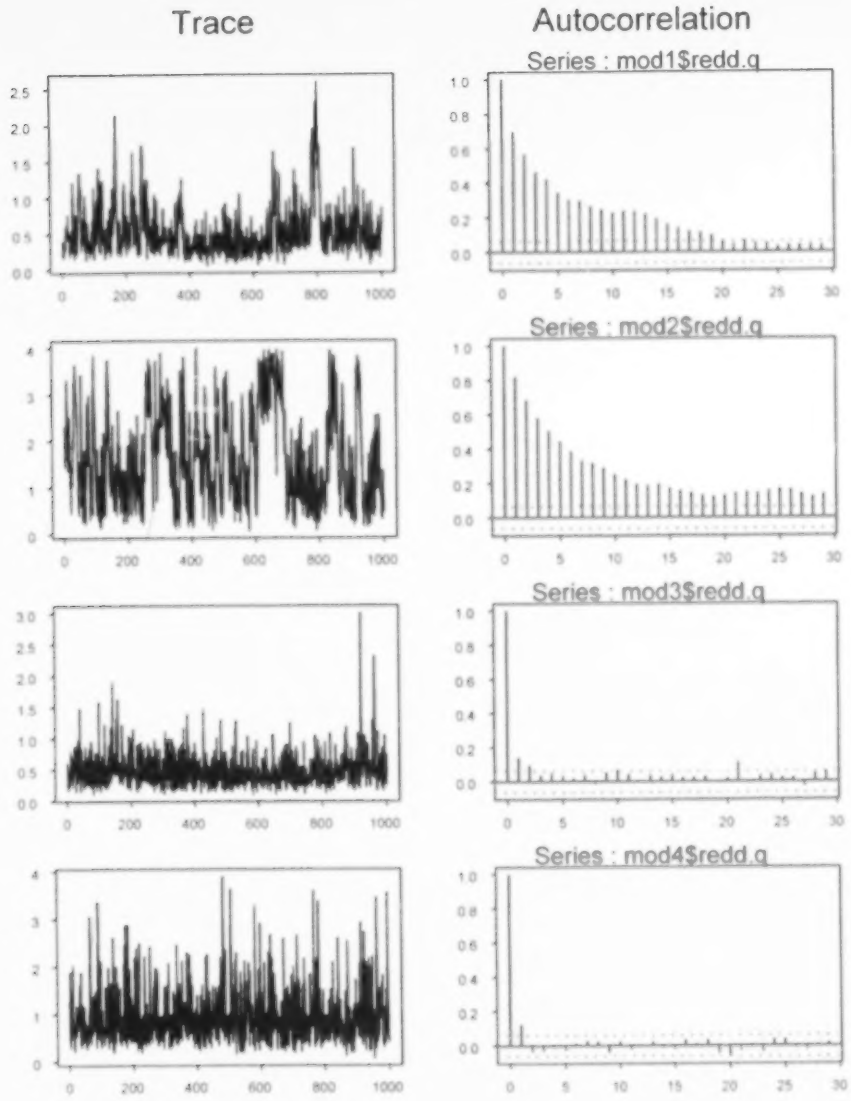

Figure A2.2. Trace and autocorrelation plots for q_{redd} for Models 1 (top) to 4 (bottom). Model formulations are described in text.

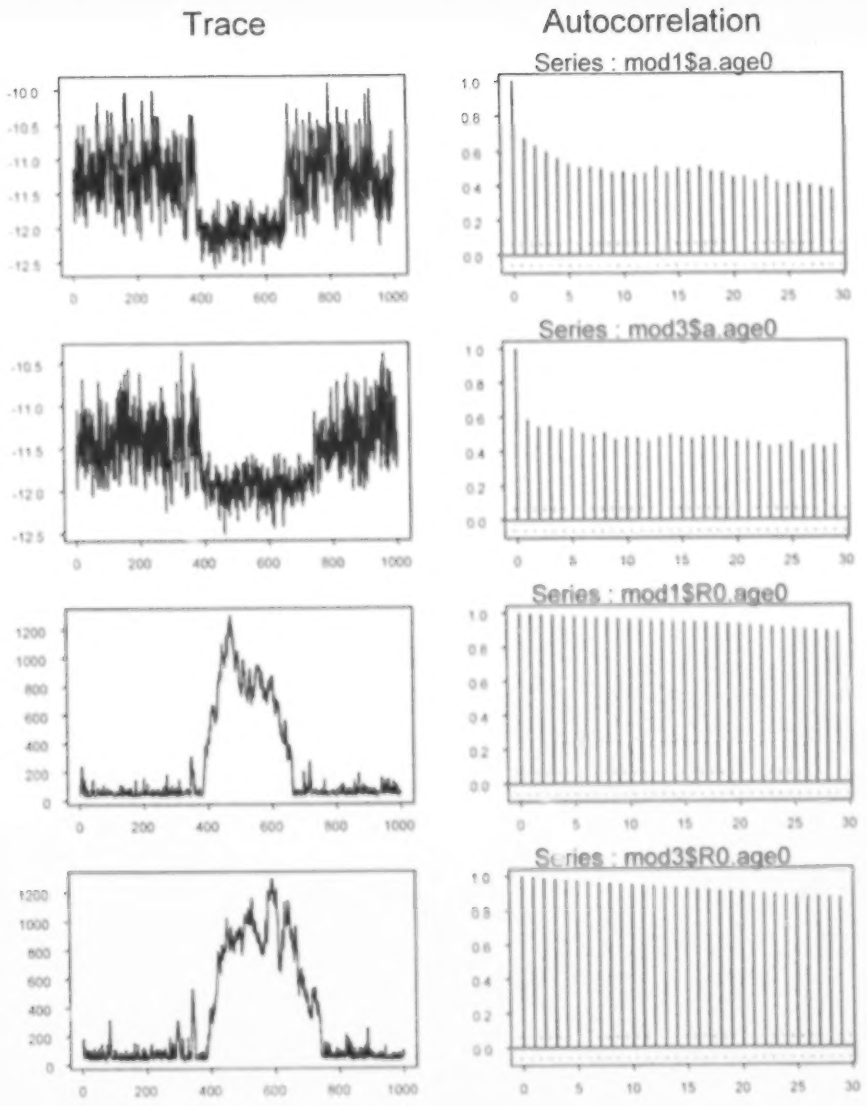

Figure A2.3. Trace and autocorrelation plots for the electrofishing coefficients (α first and second rows, and R_0 third and last rows) for age-0 salmon from Models 1 (rows 1 and 3) and 3 (rows 2 and 4).

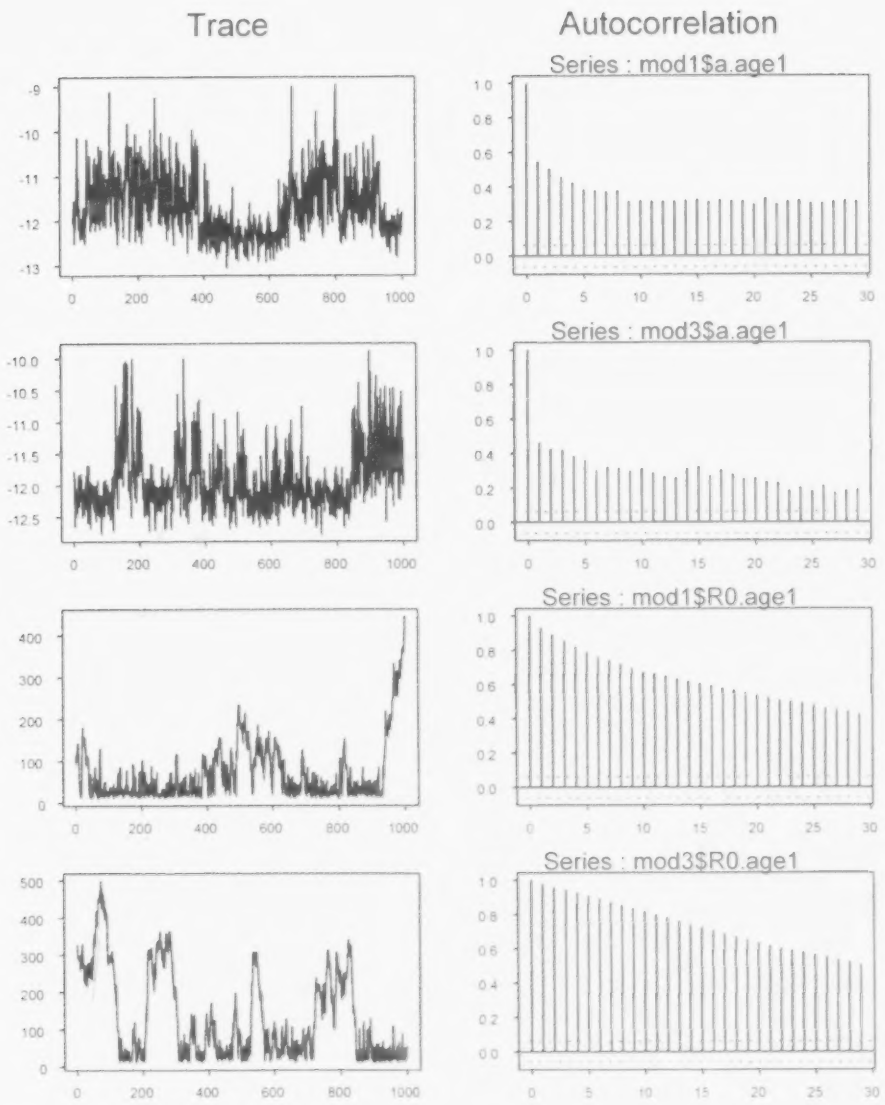

Figure A2.4. Trace and autocorrelation plots for the electrofishing coefficients (α first and second rows, and R_0 third and bottom row) for age-1 salmon from Models 1 (rows 1 and 3) and 3 (rows 2 and 4).

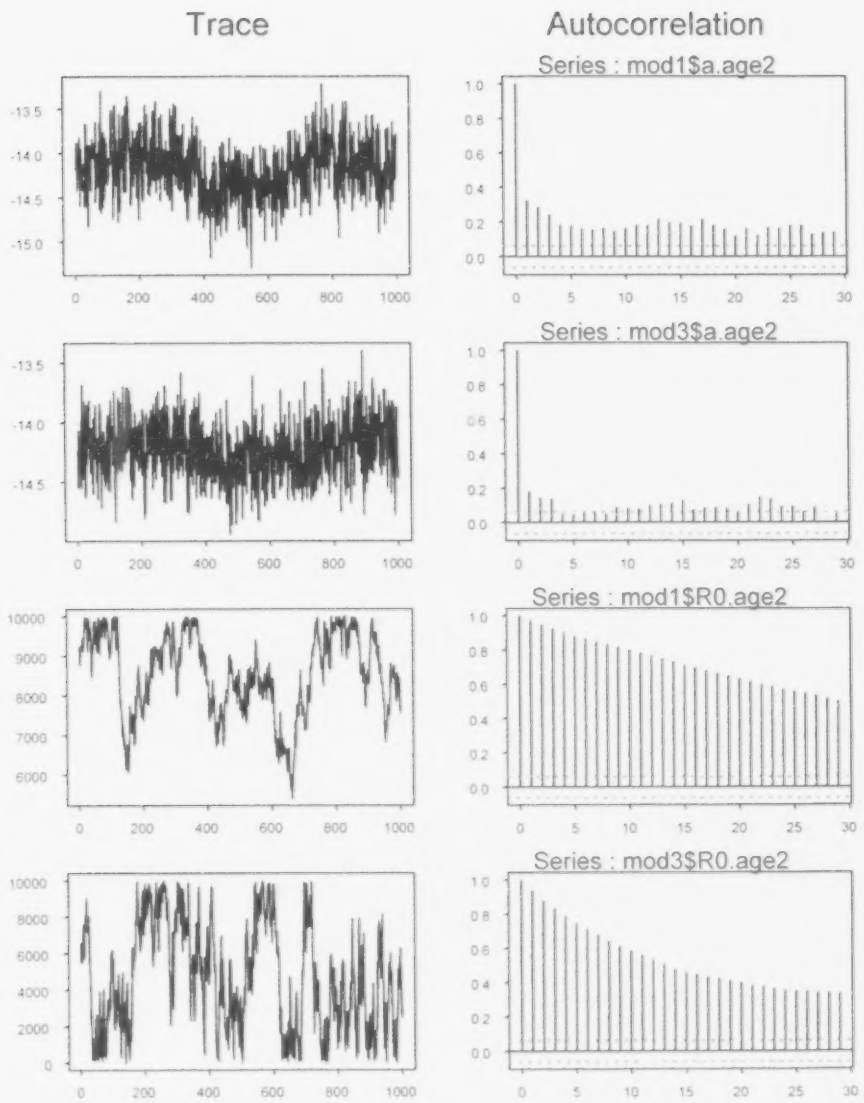

Figure A2.5. Trace and autocorrelation plots for the electrofishing coefficients (α first and second rows, and R_0 third and bottom rows) for age-2 salmon from Models 1 (rows 1 and 3) and 3 (rows 2 and 4).

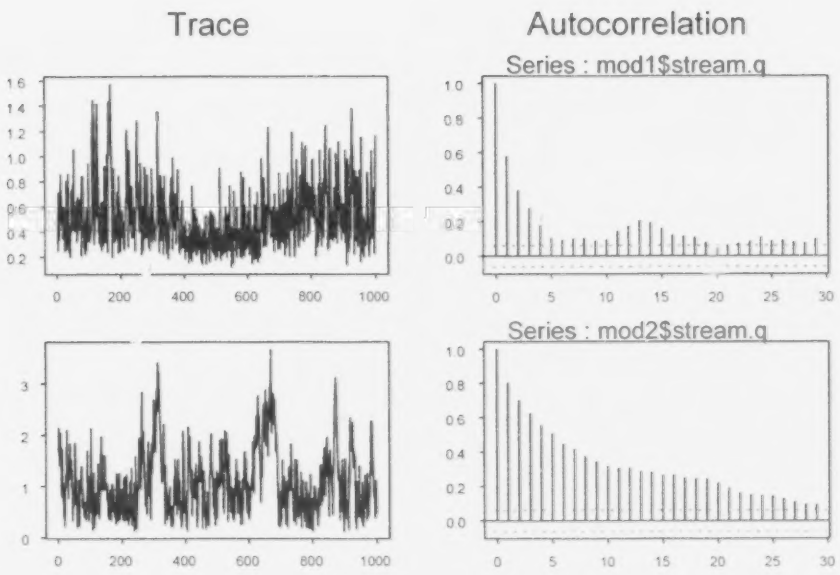

Figure A2.6. Trace and autocorrelation plots for the shoreline and dive observability coefficient, q_{swim}, from Model 1 (top row) and Model 2 (bottom row). The electrofishing component of the model is included in Model 1 but not Model 2.

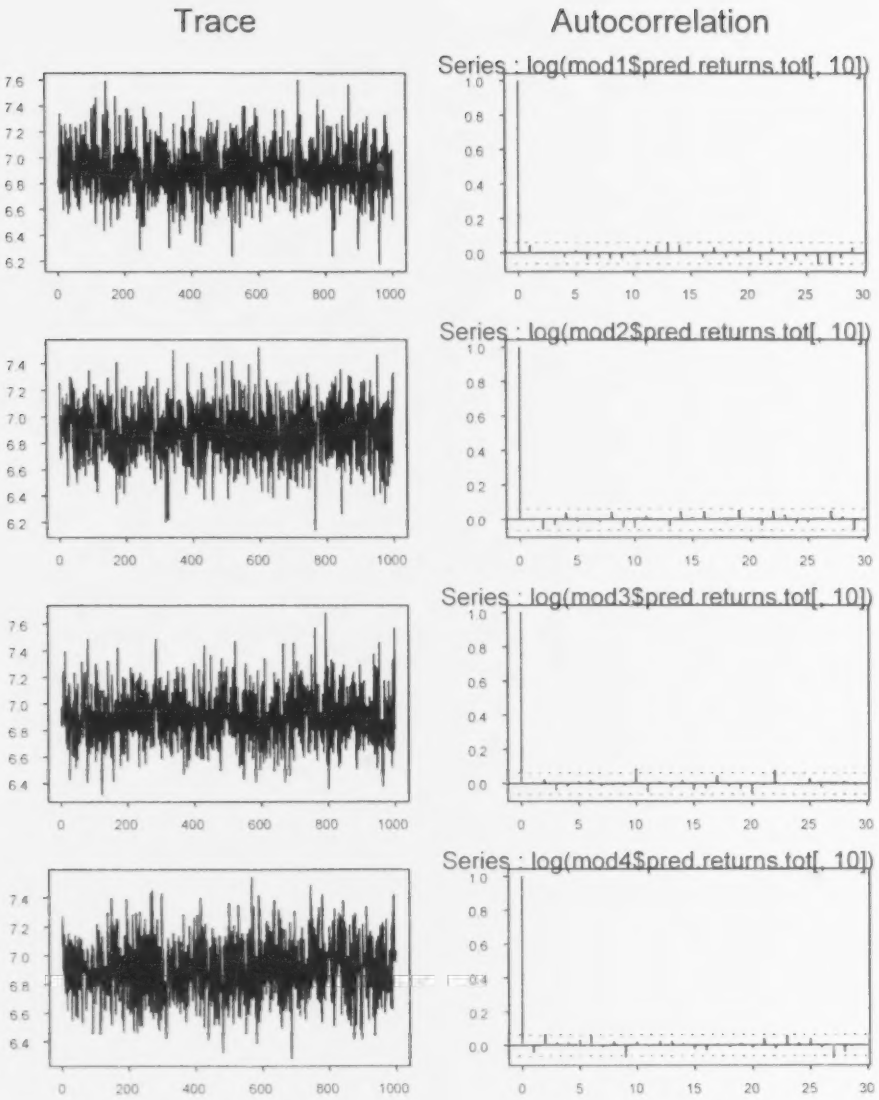

Figure A2.7. Trace and autocorrelation plots for the logarithm of the number of fish returning to the Big Salmon River in 1974, from Models 1 (top) to 4 (bottom). Model formulations are described in text.

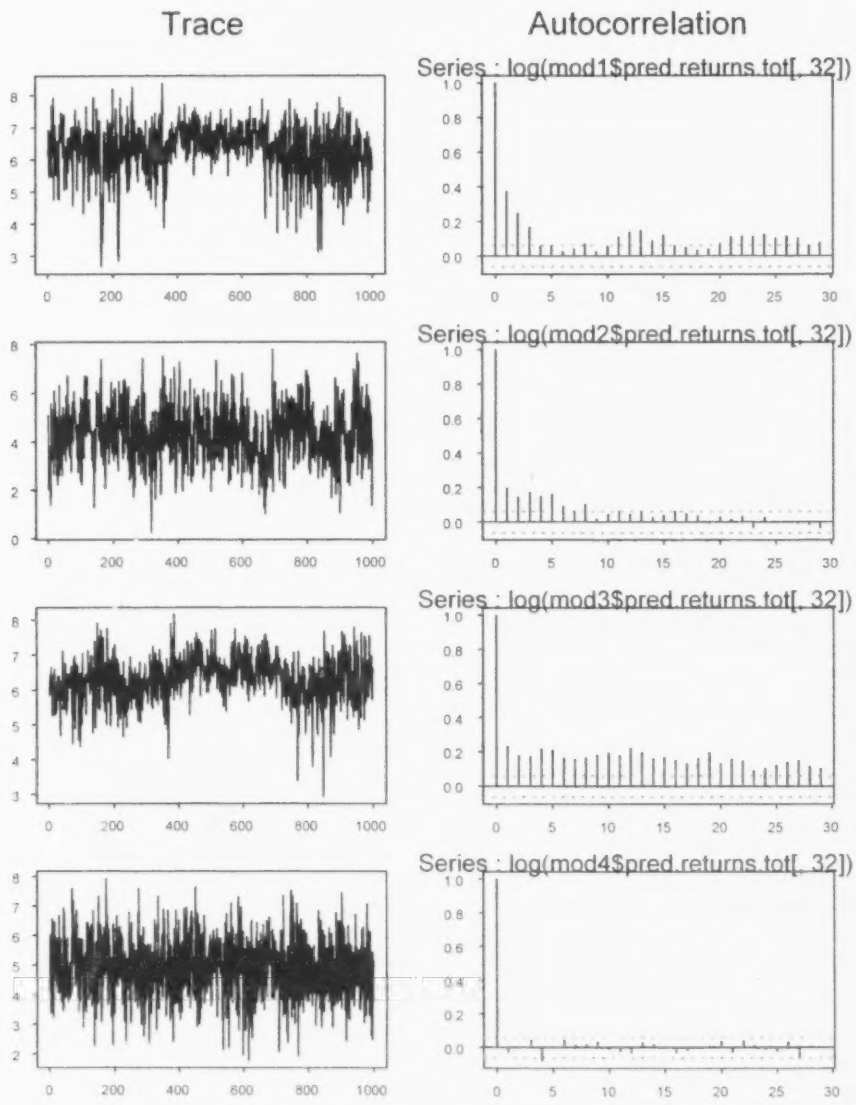

Figure A2.8. Trace and autocorrelation plots for the logarithm of the number of fish returning to the Big Salmon River in 1996, from Models 1 (top) to 4 (bottom). Model formulations are described in text.

Appendix 3. Big Salmon River dive observations and seining activities, 2000-2002. River sections and pool locations are shown in Figure 3.

Date	Pool	Section	Gear	Water conditions		Salmon observed				Salmon sampled			
				Visibility	Level	Large	Small	Total		MSW	1SW	Total
Aug. 30, 2000	all	lower	snorkel	excellent	low	4	21	25		-	-	-
Oct. 16, 2000	Walton Dam	upper	snorkel, seine	good	low	1	4	5		1	4	5
	King	upper	snorkel	good	low	0	0	0		0	0	0
	Upper Bridge	upper	snorkel	good	low	0	0	0		0	0	0
Oct. 17, 2000	Gravelly Brook	upper	snorkel, seine	good	low	0	3	3		0	2	2
	Walker Brow	upper	snorkel, seine	good	low	0	4	4		0	2	2
Oct. 18, 2000	all	lower	snorkel, seine	good	low	4	12	16		0	2	2
						5	23	28		1	10	11
Oct. 19, 2000	all	upper	snorkel	very poor	high	0	1	1		-	-	-
	all	middle	snorkel	very poor	high	0	0	0		-	-	-
	all	lower	snorkel	very poor	high	0	0	0		-	-	-
Aug. 23, 2001	8 pools	lower	snorkel	-	-	0	8	8		-	-	-
Oct. 16, 2001	Walton Dam	upper	snorkel	excellent	low	0	0	0		-	-	-
	Gravelly Brook	upper	snorkel	excellent	low	0	0	0		-	-	-
	Walker Brow	upper	snorkel	excellent	low	0	0	0		-	-	-
Oct. 16, 2001	all	lower	snorkel	excellent	low	8	7	15		-	-	-
Oct. 22, 2001	all	lower	snorkel	excellent	low	2	8	10		-	-	-
Oct. 23, 2001	all	upper	snorkel	excellent	low	3	3	6	a	-	-	-
	all	middle	snorkel	excellent	low	3	1	4		-	-	-
						8	12	20		0	0	0
Aug. 27, 2002	all	lower	snorkel	excellent	low	5	12	17	b	-	-	-
Sept. 03, 2002	Walton Dam	upper	snorkel	excellent	low	0	0	0		-	-	-
	Gravelly Brook	upper	snorkel	excellent	low	0	4	4		-	-	-
	Walker Brow	upper	snorkel	excellent	low	0	0	0		-	-	-
						5	16	21				
Sept. 18, 2002	Rody Bar	lower	snorkel, seine, scuba	good	low/mod	0	0	0				
	Rody	lower	snorkel, seine, scuba	good	low/mod	3	2	5		1	1	2
	Catt	lower	snorkel, seine, scuba	good	low/mod	3	2	5	c	2	1	3
	Tidal	lower	snorkel, seine, scuba	good	low/mod	0	0	0				
Sept. 19, 2002	Upper Bridge	upper	snorkel	good	low/mod	0	0	0		-	-	-
	Walton Dam	upper	snorkel	good	low/mod	0	0	0		-	-	-
	Gravelly Brook	upper	snorkel	good	low/mod	0	0	0		-	-	-
	Walker Brow	upper	snorkel	good	low/mod	0	0	0		-	-	-
						6	4	10				
Oct. 23, 2002	all	upper	snorkel	good	moderate	0	0	0		-	-	-
	all	middle	snorkel	good	moderate	0	0	0		-	-	-
	all	lower	snorkel	good	moderate	0	2	2	d	-	-	-
Oct. 24, 2002	all	headwaters	snorkel/walk	good	moderate	0	0	0		-	-	-
						0	2	2		3	2	5

NOTES

[a] 1 large salmon was tagged with a yellow disc tag, applied in 2000

[b] 2 large / 5 small in Rody pool, 3 large / 7 small in Catt pool

[c] 2 tagged & scaled; 1 scaled & released untagged

[d] 1 untagged + 1 tagged